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Budd

TECHNICAL PROGRESS REPORT

CONTRACT DA-36-034-ORD-3296 RD

ORDNANCE CORPS PROJECT NUMBER — OMS 5010.1180 800.51.03

PREPARED FOR

U. S. ARMY ORDNANCE DISTRICT

PHILADELPHIA, PA.

UNDER

TECHNICAL SUPERVISION — FRANKFORD ARSENAL

CONTROL NO. A5180

DEVELOPMENT OF HIGH PERFORMANCE ROCKET MOTOR CASE

QUARTERLY REPORT NUMBER 18

Period — October 1, 1961 to December 31, 1961

PRODUCT DEVELOPMENT DEPARTMENT

THE BUDD COMPANY

Philadelphia 32, Pennsylvania

THE Budd COMPANY

PHILADELPHIA 32, PA.

PRODUCT DEVELOPMENT

ENGINEERING
QUARTERLY PROGRESS REPORT NO. 18

Period: October 1, 1961 to December 31, 1961

Contract: DA-36-034-ORD-3296RD

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ROCKET MOTOR CASE DEVELOPMENT

Control No. A-5180

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A B S T R A C T

The objective of this program is to develop a solid propellant rocket motor case having the following characteristics:

1. A minimum diameter of 40 inches and a length to diameter ratio of 2:1.

2. An overall strength to weight ratio of 1×10^6 inch or more.

3. Utilize sheet or strip metal in condition of maximum usable strength requiring a minimum of post fabrication heat treatment.

The design objective is being attained through the following program:

1. Material investigation, evaluation and selection.

2. Weld joint evaluation of selected alloys.

3. Design, manufacture and hydrotest of 20 inch diameter chambers.

4. Design, manufacture and hydrotest of 40 inch diameter prototype chambers.

Evaluation of twelve alloys has been completed. The following alloys were selected for the 20 inch diameter chambers based on the data obtained:

1. Ti 13V-11Cr-3Al alloy, cold rolled and aged to a minimum yield strength of 210,000 psi.

2. 20% nickel steel of a special analysis having 1.7 titanium and 0.5 aluminum in the composition. This material is cold rolled and aged to attain a minimum yield strength of 310,000 psi.

Both alloys are currently in process at the mills. An additional evaluation is being conducted on the 20% nickel steel to determine the combination of cold reduction, aging temperature and aging time that will yield optimum tensile and fracture toughness values. Evaluation of the Ti 13V-11Cr-3Al alloy has been limited, due to the availability of data obtained from other contractors.

The 20 inch diameter chamber design uses 12 inch wide strip material, single thickness, butt welded, with the weld angle oriented 11 degrees to the direction of maximum hoop stress. The resultant normal stress in the weld, due to pressurization of the cylinder, will be lower than the as welded or as welded and aged strength of the

base metal.

The cylinder is helical butt welded in a fixture designed for this program. Strip is fed continuously through drive rolls at the proper helix angle. The TIG weld is made at the point where the incoming strip joins the adjacent wrapped section of the cylinder. Elliptical heads are cold formed using a newly developed proprietary sandwich draw technique.

Delivery of strip for the 20 inch diameter chamber is anticipated during the first quarter 1962. Based on these deliveries, burst tests of the 20 inch titanium and nickel steel chambers are scheduled for the same quarter.

CONTENT SUMMARY

This is the eighteenth progress report covering the work being conducted under Contract DA-36-034-ORD-3296RD by The Budd Company. The report includes the work accomplished during the quarterly period October 1, 1961 to December 31, 1961 and will serve as the monthly progress report for December, 1961.

Work during the quarterly period was primarily directed toward the manufacture of four 20 inch diameter test chambers. A modified analysis of International Nickel Company's 20% nickel steel will be used on two test chambers and two will be fabricated from the Ti 13V-11Cr-3Al alloy. Design drawings were completed during the period and are included in this report.

Tooling for the 20 inch diameter test chamber is approximately 80% complete. The special fixture for welding the helical butt weld in the cylindrical section is undergoing tryout.

Additional evaluation of the 20% nickel steel of modified higher titanium analysis was initiated during the quarter. Using material available from the initial procurement, we are studying the effect on tensile and fracture

toughness of aging at temperatures ranging from 750°F to 1000°F in 50°F increments at 3 hours. Using the optimum aging temperatures, tensile and frac ture toughness specimens will be aged at times of 1, 2 and 4 hours to determine the effect of aging time on properties. Available data are included in this report.

As a second phase of the 20% nickel evaluation, it is planned to determine the effect on mechanical properties and fracture toughness of various amounts of cold reduction. Approximately 90 pounds of material ordered for the 20 inch diameter chambers will be diverted and will be processed to the .040 inch thickness from .160 inch thick hot band in reductions of 30%, 40%, 50%, 60%, 70% and 75% to final thickness. Aging temperatures from 800°F to 1000°F will be used on material from each reduction and the effect on properties will be determined.

Ti 13V-11Cr-3Al and 20% nickel steel have been ordered for the four 20 inch diameter test chambers. Process delays at the mills have set back delivery estimates on these materials until late January or early February, 1962.

The research work at Massachusetts Institute of

Technology on controlled ingot solidification continued during the period. M.I.T. report numbers 3, 4 and 5, covering work accomplished during October, November and December, 1961, are included herein.

MATERIAL EVALUATION

General Discussion of 20% and 25% Nickel Steels, High Titanium Composition

The basic characteristics of the 20% and 25% nickel steels were discussed in Report No. 4, issued in November, 1960. The compositions of these materials are shown in Table 1. At that time, these analyses were considered to be "standard" and compared reasonably well with the compositions of most of the high nickel steels being evaluated by other investigators.

Additional discussion and test data of these two grades may be found in subsequent reports. The 25% nickel alloy was covered in Report No. 9, April, 1961 and discussion of the 20% nickel and 25% nickel steels may be found in Report No. 11, June, 1961.

As our own test results became available, as well as test data from other investigators, it became apparent that the "standard" analysis would not be

adequate for the strength level required by our design concept. Therefore, after consultation with The International Nickel Company, we adopted, at their suggestion, a modified composition of both the 20% and 25% nickel grades which they felt could be processed to the required strength levels. The modification of the analyses consisted primarily of an increase in the hardener element content. These elements are titanium, aluminum and columbium. In addition, elements known to have adverse effects, such as silicon and manganese, were reduced to lower allowable percentages. Boran and zirconium in small amounts were added for other effects. The compositions of the modified grades are also shown in Table 1, where comparison with the "standard" analyses can be made.

Material of each grade was purchased from Allegheny-Ludlum Corporation as the product of 2000 pound ingots. Both the 20% and 25% nickel heats were vacuum induction primary melted and vacuum consumable electrode re-melted. Approximately 1200 pounds of finished product were realized from each heat.

CHEMICAL COMPOSITIONS

STANDARD AND MODIFIED 20% AND 25% NICKEL STEELS*

	"Standard" Grades		High Ti Modified Grades	
	20% Ni Ht. No. 23222-1	25% Ni Ht. No. 23223-1	20% Ni Ht. No. 23579-1	25% Ni Ht. No. 23569-1
Carbon	0.007	0.006	0.019	0.018
Manganese	0.105	0.120	0.010	0.010
Phosphorus	0.007	0.008	0.002	0.001
Sulphur	0.002	0.002	0.002	0.001
Silicon	0.15	0.17	0.010	0.010
Columbium	0.52	0.54	0.60	0.600
Nickel	20.04	25.33	19.96	25.18
Titanium	1.27	1.37	1.72	1.72
Aluminum	0.22	0.20	0.50	.50
Boron	-	-	0.004	0.004
Zirconium	-	-	0.019	0.015
Iron	Bal.	Bal.	Bal.	Bal.

* All heats produced by
Allegheny-Ludlum Steel Corporation by

1. Vacuum induction primary melt
(and)2. Vacuum consumable electrode re-melt

TABLE 1 The Budd Co. 1-62

The materials were received in various gages and conditions, as shown below:

Thickness - Inches	20% Ni	20% Ni
0.125	Annealed	Annealed
0.075	Annealed	Annealed
0.075	Cold Rolled*	Cold Rolled*
0.032	Cold Rolled*	Cold Rolled*

*Cold rolled to 65% reduction.

All the stock was rolled to 19 inch wide strip and supplied in approximately 100 inch cut lengths.

The properties of each grade and the test data will be separately discussed in the following sections.

20% Nickel Steel, High Titanium Modification

The 0.125 inch thick 20% nickel sheet stock was initially used to establish heat treating procedures. Two treatments were developed, based on procedures used for other analyses of the basic 20% nickel alloy. In an attempt to develop maximum strength, the following treatments were used:

A - 1. Material in the 1500°F annealed condition.

2. Cool at -100°F, 16 hours minimum; air warm.

3. Mar-age at 850°F, 1 hour; air cool.

B - 1. Re-anneal at 1500°F, 15 minutes; cool in furnace to 1100°F, 8 hours; air cool.

2. Cool at -100°F, 16 hours minimum; air warm.

3. Mar-age at 850°F, 1 hour; air cool.

Tensile test results of the 0.125 inch thick sheet stock after receiving the above treatments showed that the material was in an extremely high strength condition, but possessing low toughness. Difficulty was experienced in the handling of test specimens. The 0.125 inch thick material sheared gripping pins and failed in areas other than in the gage length. Specimens that did fail in the gage length exhibited no yielding prior to fracture.

The heat treatments were altered to reduce the hardening response and to develop tensile yield strengths in the vicinity of 300,000 to 310,000 psi. Another group of 0.125 inch thick tensile specimens were heat treated, according to the following procedures:

A - 1. Material in the 1500°F annealed condition.

2. Cool at -100°F, 16 hours minimum; air warm.

3. Mar-age at 900°F, 1 hour; air cool.

B - 1. Re-anneal at 1500°F, 15 minutes, cool in furnace to 1150°F, 8 hours; air cool.

2. Cool at -100°F, 16 hours minimum; air warm.

3. Mar-age at 950°F, 2 hours; air cool.

The response to these heat treatments was much more satisfactory, with the isothermal treatment (Type R), developing significantly better ductility at a higher strength. These data may be seen in Table 2. The mill annealed properties of the 0.125 inch and 0.075 inch material are shown in Table 3.

After processing the 0.125 inch material, the heat treatments, which had been found acceptable, were applied to the 0.075 inch annealed 20% nickel. Tensile specimens and center notched fracture energy specimens were made and tested. The heat treatments used are shown above on this page. Table 4 shows the tensile properties and Tables 5 and 6 show the fracture energy data of the 0.075 inch thick specimens.

MECHANICAL PROPERTIES OF 20% NICKEL STEEL

HIGH Ti COMPOSITION

Heat Number 23579-1

0.125" Gage

Condition	Spec. No.	Direct.	Yield Strength 0.2% Offset KSI	Ult. Tensile Strength KSI	%Elong. in 2 Inches	Rockwell Hardness
Mill Annealed	HLAL-5	L	298	312	3.0	RC 55
-100°F, 16 Hrs.	HLAL-6	L	306	320	1.5*	
900°F, 2 Hrs.	HLAL-7	L	300	310	0.5*	
	HLAL-8	L	299	308	0.5*	
	HLAT-5	T	308	318	0.5*	
	HLAT-6	T	311	320	2.0*	
	HLAT-7	T	306	316	0.5*	
	HLAT-8	T	310	318	0.5*	
1500°F, 15 Mins.	HRAL-5	L	306	333	4.5	RC 59-60
	HRAL-6	L	291	336	3.0	
Furnace Cooled to 1150°F, 8 Hrs.	HRAL-7	L	304	335	4.5	
-100°F, 16 Hrs.						
950°F, 2 Hrs.	HRAT-5	T	312	353	3.5	
	HRAT-6	T	328	353	2.5	
	HRAT-7	T	312	357	3.0	

* Specimen broke outside of gage length

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TABLE 2

MECHANICAL PROPERTIES OF 20% NICKEL STEEL

HIGH Ti COMPOSITION

Gage as Noted

Heat Number 23579-1

Condition	Spec. No.	Direct.	Yield Strength 0.2% Offset KSI	Ult. Tensile Strength KSI	% El. in 2 Inches	Rockwell Hardness
Mill Annealed*	HAAL-1	L	121	194	8.5	RC 40-41
0.075"	HAAL-2	L	117	194	8.5	
	HAAL-3	L	122	194	8.0	
	HAAL-4	L	121	195	9.0	
	HAAT-1	T	122	204	7.5	
	HAAT-2	T	123	203	8.0	
	HAAT-3	T	126	204	7.5	
	HAAT-4	T	125	204	7.5	
Mill Annealed*	HAAL-1	L	125	172	10.0	RC 40-41
0.125"	HAAL-2	L	128	173	9.5	
	HAAL-3	L	129	173	10.0	
	HAAL-4	L	130	172	9.0	
	HAAT-1	T	135	178	8.0	
	HAAT-2	T	136	182	8.5	
	HAAT-3	T	136	180	7.5	
	HAAT-4	T	143	180	7.5	

* 1500° F, air cooled

TABLE 3

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MECHANICAL PROPERTIES OF 20% NICKEL STEEL

HIGH Ti COMPOSITION

Heat Number 23579-1

0.075" Gage

Condition	Spec. No.	Direct.	Yield Strength 0.2% Offset KSI	Ult. Tensile Strength KSI	% Elong. in 2 Inches	Rockwell Hardness
Mill Annealed	HLAL-1	L	325	333	3	RC 57
-100°F, 16 Hrs.	HLAL-2	L	326	336	3	
900°F, 2 Hrs.	HLAL-3	L	335	343	2.5	
	HLAL-4	L	324	332	3	
	HLAT-1	T	337	348	-	RC 57
	HLAT-2	T	336	350	2.5	
	HLAT-3	T	350	356	-	
	HLAT-4	T	341	350	1.5	
1500°F, 15 Mins.	HRAL-1	L	319	326	4	RC 56.5
Furnace Cooled	HRAL-2	L	310	319	3	
to 1150°F, 8 Hrs.	HRAL-3	L	312	321	3	
-100°F, 16 Hrs.	HRAL-4	L	315	322	3	
950°F, 2 Hrs.	HRAT-1	T	326	335	2	RC 56.5
	HRAT-2	T	335	344	2	
	HRAT-3	T	335	344	-	
	HRAT-4	T	336	344	-	

TABLE 4

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FRACTURE ENERGY PROPERTIES OF 20% NICKEL STEEL
HIGH Ti COMPOSITION

Heat Treated*
Heat Number 23579-1

Center Notched Specimen
(Dwg. No. 2434-0014)
0.075" Gage

Spec. No.	Direct.	Yield Strength KSI $\sigma_{Y.S.}$	Ult. Strength KSI $\sigma_{Ult.}$	% El. in 2 Inches	K_{C1} PSI $\sqrt{\text{Inch}}$	$\frac{\sigma_{Y.S.}}{d} \times 10^6$
HLBL-1	L	327	336	3	37,000	1.18
HLBL-2	L	327	336	3	39,000	1.18
HLBL-3	L	327	336	3	36,000	1.18
HLBL-4	L	327	336	3	39,000	1.18
				Aver.	37,800	
HLBT-1	T	341	351	2	39,000	1.24
HLBT-2	T	341	351	2	35,000	1.24
HLBT-3	T	341	351	2	36,000	1.24
HLBT-4	T	341	351	2	39,000	1.24
				Aver.	37,250	

*Mill annealed
-100°F, 16 hrs., air warmed
900°F, 2 hrs., air cooled

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TABLE 5

FRACTURE ENERGY PROPERTIES OF 20% NICKEL STEEL

HIGH Ti COMPOSITION

Heat Treated*
Heat Number 23579-1

Center Notched Specimen (Dwg. No. 2434-0014)
0.075" Gage

Spec. No.	Direct.	Yield Strength KSI $\sigma_{Y.S.}$	Ult. Strength KSI $\sigma_{Ult.}$	% El. in 2 Inches	K_{C1} PSI$\sqrt{\text{Inch}}$	$\frac{\sigma_{Y.S.}}{\text{density}}$ X 10^6
HRBL-1	L	314	322	3.2	49,000	1.13
HRBL-2	L	314	322	3.2	52,000	1.13
HRBL-3	L	314	322	3.2	61,000	1.13
HRBL-4	L	314	322	3.2	56,000	1.13
				Aver.	54,500	
HRBT-1	T	335	342	2	53,000	1.20
HRBT-2	T	335	342	2	50,000	1.20
HRBT-3	T	335	342	2	48,000	1.20
HRBT-4	T	335	342	2	46,000	1.20
				Aver.	49,200	

* 1500°F, 15 min., furnace cooled
to 1150°F, 8 hrs., air cooled
-100°F, 16 hrs., air warmed
950°F, 2 hrs., air cooled

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TABLE 6

The tensile strengths of the 0.075 inch material are higher than the similarly treated 0.125 inch stock. Both the straight aging process and the isothemal treatment developed yield strengths in excess of 300,000 psi.

The fracture toughness as indicated by K_{C1} values indicates that the isothermally treated specimens exhibit from 32% to 44% better toughness than the straight aged material. However, the straight aged material was at a greater strength level. The apparent improvement obtained with the isothermal aging treatment will be more fully investigated in the next quarter.

We had also ordered and received 20% nickel steel (high Ti composition) in the cold rolled condition. Limited mill tensile testing of cold rolled sheet stock had indicated that a 65% reduction was the most suitable for both the 20% and 25% nickel alloys. Therefore, we requested 0.075 inch and 0.032 inch material cold reduced to that amount. Final heat treated properties obtained by the mill were based on aging at 850°F for 2 hours.

The cold rolled material was aged in our own plant at 850°F for 3 hours. Both tensile specimens and center notched fracture energy specimens were tested. The tensile properties and hardness are shown in Table 7, and the fracture energy data of similarly treated material are shown in Tables 8 and 9.

The lighter gage sheet exhibited higher tensile strength in both the longitudinal and transverse directions. The fracture toughness and ductility of the heavier material was greater.

In order to more fully understand the effect of aging time and temperatures, a testing program was set up using tensile and fracture energy specimens. The specimens were made from the 0.032 inch thick cold rolled material and were aged in fifty degree increments from 750°F to 1000°F, for 3 hours. Specimens were also aged at 950°F for 1, 2 and 4 hours to evaluate the effect of aging time, at a given temperature. The tensile test data are shown in Tables 10 and 11, and are graphically shown in Figure Numbers 1 and 2. The K_{C1} values, representing fracture toughness will be found in Tables 12 and 13, and plotted versus aging temperatures in Figure No. 3.

MECHANICAL PROPERTIES OF 20% NICKEL STEEL

HIGH Ti COMPOSITION

Cold Rolled 65%
-100°F, 16 hrs: 850°F, 3 hrs.

Heat No. 23579-1
Gage as noted

Gage	Spec. No.	Direct	Yield Strength 0.2% Offset KSI	Ult. Tensile Strength KSI	% El. in 2 Inches	Rockwell Hardness
0.033"	HNAL-1	L	350	377	2.0	RC 59-60
	HNAL-2	L	331	360	1.0+	
	HNAL-3	L	345	353	1.0+	
	HNAL-4	L	348	356	0.5	
	HNAT-1	T	376	382	0.5	
	HNAT-2	T	378	388	-	
	HNAT-3	T	376	386	Nil	
	HNAT-4	T	375	386	1.0+	
0.075"	HNAL-1	L	330	333	2.5	RC 58
	HNAL-2	L	326	332	2.0	
	HNAL-3	L	-	329	2.0	
	HNAL-4	L	-	329	2.5	
	HNAT-1	T	335*	362	-	
	HNAT	T	340*	363	-	
	HNAT	T	340*	360	-	
	HNAT	T	353*	362	-	

TABLE 7

* Y.S. Estimated

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FRACTURE ENERGY DATA OF 20% NICKEL STEEL

HIGH Ti COMPOSITION

Cold Rolled and Aged*
Heat No. 23579-1

Center Notched Specimen (Dwg. No. 2434-0014)
0.033" Gage

Spec. No.	Direct.	Yield Strength KSI $\sigma_{Y.S.}$	Ult. Strength KSI $\sigma_{Ult.}$	% El. in 2 Inches	K_{Cl} PSI$\sqrt{\text{Inch}}$	$\frac{\sigma_{Y.S.}}{\text{density}}$ X 10^6
HNBL-1	L	344	358	1.0+	38,000	1.21
HNBL-2	L	344	358	1.0+	49,000	1.21
HNBL-3	L	344	358	1.0+	40,000	1.21
HNBL-4	L	344	358	1.0+	54,000	1.21
				Aver.	45,000	
HNBT-1	T	376	385	0.5	-	1.32
HNBT-2	T	376	385	0.5	-	1.32
HNBT-3	T	376	385	0.5	25,000	1.32
HNBT-4	T	376	385	0.5	24,000	1.32
				Aver.	24,500	

* Cold Rolled 65%
Sub-Zero Cooled -100°F, 16 Hrs.
Aged 850°F, 3 Hrs., Air Cooled

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TABLE 8

FRACTURE ENERGY DATA OF 20% NICKEL STEEL

HIGH Ti COMPOSITION

Cold Rolled and Aged*
Heat No. 23579-3

Center Notched Specimen
(Dwg. No. 2434-0014)
0.075" Gage

Spec. No.	Direct.	Yield Strength KSI $\sigma_{Y.S.}$	Ult. Strength KSI $\sigma_{Ult.}$	% El. in 2 Inches	K_{CI} PSI $\sqrt{\text{Inch}}$	$\frac{\sigma_{Y.S.}}{\text{density}}$ X 10^6
HNBL-1	L	328	331	2.5	51,000	1.15
HNBL-2	L	328	331	2.5	58,000	1.15
HNBL-3	L	328	331	2.5	63,000	1.15
HNBL-4	L	328	331	2.5	56,000	1.15
				Aver.	57,000	
HNBT-1	T	345	362	Nil	33,000	1.21
HNBT-2	T	346	362	Nil	30,000	1.21
HNBT-3	T	345	362	Nil	31,000	1.21
HNBT-4	T	345	362	Nil	36,000	1.21
				Aver.	33,000	

*Cold Rolled 65%
Sub-Zero Cooled -100°F, 16 Hrs.
Aged 850°F, 3 Hrs., Air Cooled

TABLE 9

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MECHANICAL PROPERTIES OF 20% NICKEL STEEL

HIGH Ti COMPOSITION

Cold Rolled 65%
Sub-Zero Cooled and Aged as Shown

Heat No. 23579-1
0.032" Gage

Aging Temp. (3 Hrs.)	No. of Tests	Direct.	Yield Strength 0.2% Offset KSI	Ult. Tensile Strength KSI	% El. in 2 Inches	Rockwell Hardness
Un-Aged	2	Long.	218	228	3	RC 42
750°F	2	Long.	340	340	-*	RC 55-56
800°F	3	Long.	350	351	-*	RC 58-59
850°F	3	Long.	349	353	-*	RC 59
900°F	3	Long.	340	347	-*	RC 58
950°F	3	Long.	318	330	2.5	RC 57-58
1000°F	2	Long.	286	307	3.5	RC 54-55

* Specimens broke outside of gage marks

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TABLE 10

MECHANICAL PROPERTIES OF 20% NICKEL STEEL

HIGH Ti COMPOSITION

Heat No. 23579-1
0.032" Gage

Cold Rolled 65%
Sub-Zero Cooled and Aged as Shown

Aging Temp. (3 Hrs.)	No. of Tests	Direct	Yield Strength 0.2% Offset KSI	Ult. Tensile Strength KSI	% El. in 2 Inches	Rockwell Hardness
Un-Aged	2	Trans.	210	242	3	RC 42
750°F	2	Trans.	357	360	-*	RC 55-56
800°F	3	Trans.	383	387	-*	RC 58-59
850°F	3	Trans.	375	378	-*	RC 59
900°F	3	Trans.	361	368	-*	RC 58
950°F	3	Trans.	351	365	1.0	RC 57-58
1000°F	2	Trans.	312	332	2.0	RC 54-55

* Specimen broke outside of gage marks

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TABLE 11

PREPARED BY:	THE BUDD COMPANY PRODUCT DEVELOPMENT PHILADELPHIA, PA.	PAGE NO. OF
CHECKED BY:		REPORT NO.
DATE:	LONG. TENSILE STRENGTH VS. AGING TEMP. (3 HOURS)	PROJECT NO.

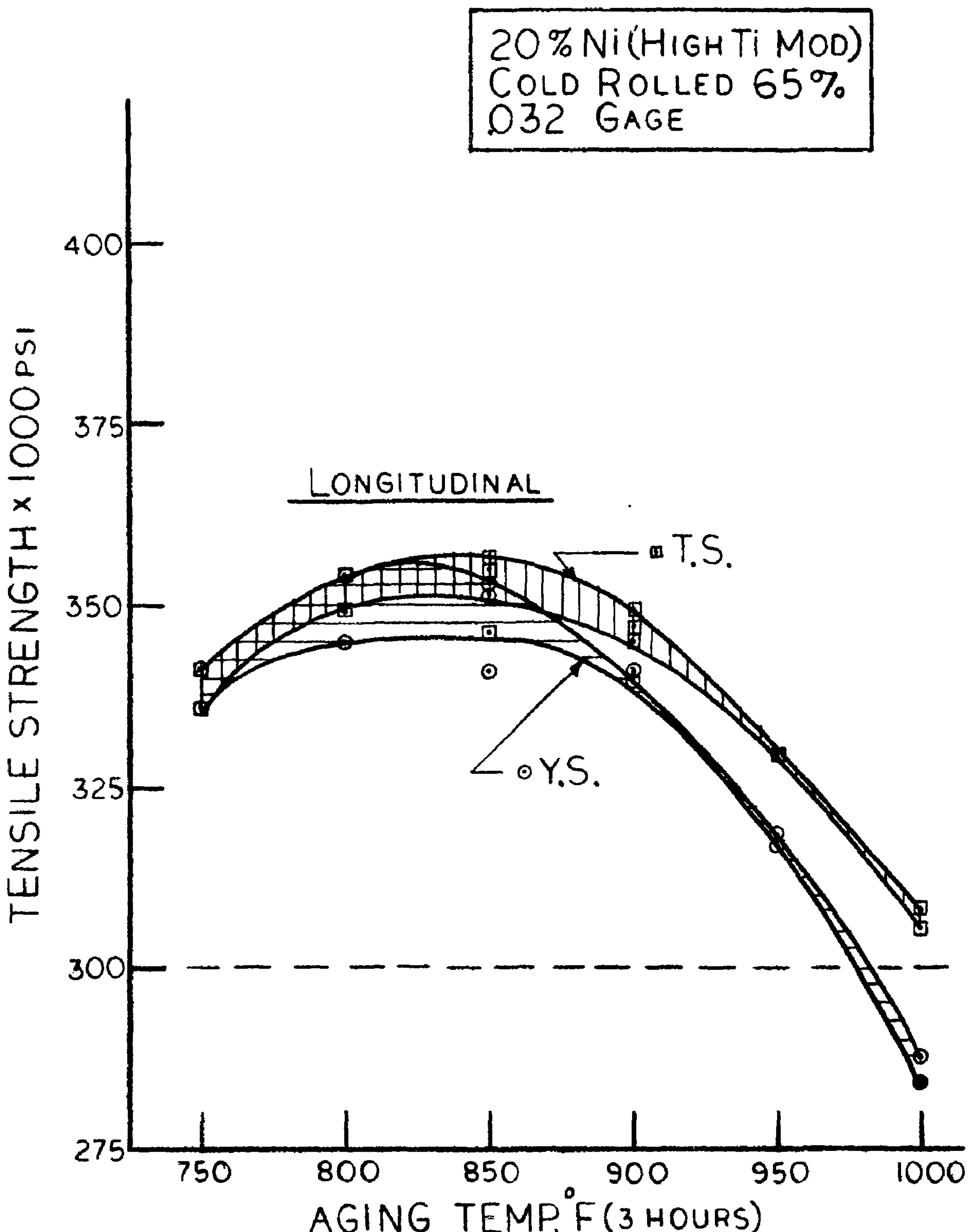

FIG. 1

PREPARED BY:	THE BUDD COMPANY PRODUCT DEVELOPMENT PHILADELPHIA, PA.	PAGE NO. OF
CHECKED BY:		REPORT NO.
DATE:	TRANS. TENSILE STRENGTH VS. AGING TEMP. (3 HOURS)	PROJECT NO.

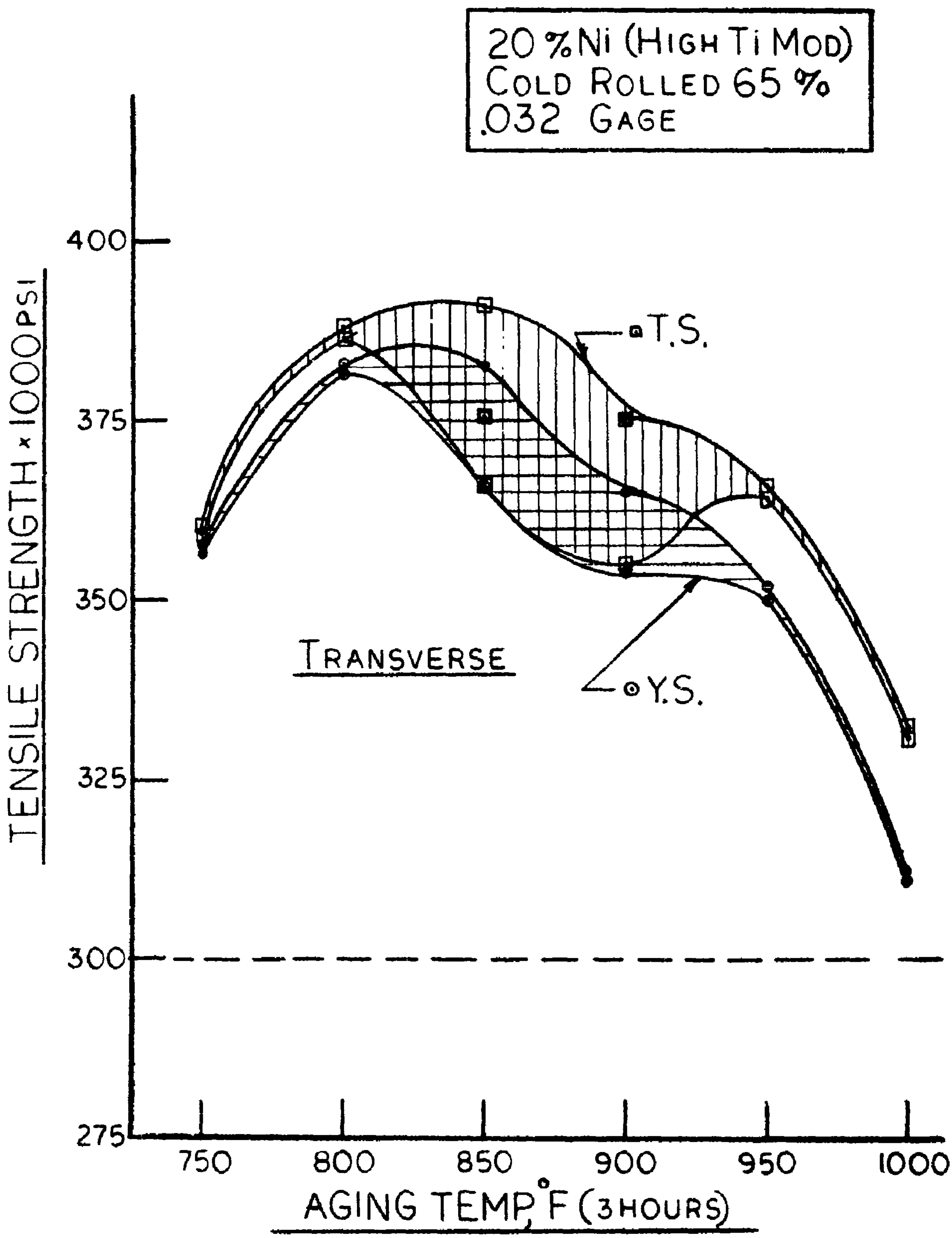

FIG. 2

FRACTURE ENERGY DATA OF 20% NICKEL STEEL

HIGH Ti COMPOSITION

Cold Rolled 65%
Sub-Zero Cooled and Aged as Shown

Heat No. 23579-1
0.032" Gage

Aging Temp. (3 Hrs.)	Spec. No.	Direct.	Yield Strength KSI $\sigma_{Y.S.}$	Ult. Strength KSI $\sigma_{Ult.}$	% El. in 2 Inches	K_{C1} PSI $\sqrt{\text{Inch}}$	$\frac{\sigma_{Y.S.}}{\text{density}}$ X 10^6
750°F	L-1	Long.	340	340	3	46,000	1.19
	L-2	Long.	340	340	3	44,000	1.19
800°F	L-3	Long.	350	351	-	42,000	1.23
	L-4	Long.	350	351	-	40,000	1.23
900°F	L-7	Long.	340	347	-	32,000	1.19
	L-8	Long.	340	347	-	39,000	1.19
950°F	L-9	Long.	318	330	2.5	38,000	1.12
	L-10	Long.	318	330	2.5	45,000	1.12
1000°F	L-11	Long.	286	307	3.5	54,000	1.00
	L-12	Long.	286	307	3.5	62,000	1.00

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TABLE 12

FRACTURE ENERGY DATA OF 20% NICKEL STEEL

HIGH Ti COMPOSITION

Heat No. 23579-1
0.032" Gage

Cold Rolled 65%
Sub-Zero Cooled and Aged as Shown

Aging Temp. (3 Hrs.)	Spec. No.	Direct	Yield Strength KSI $\sigma_{Y.S.}$	Ult. Strength KSI $\sigma_{Ult.}$	% El. in 2 Inches	K_{C1} PSI $\sqrt{\text{Inch}}$	$\frac{\sigma_{Y.S.}}{\text{density}}$ X 10^6
750°F	T-1	Trans.	357	360	3	33,000	1.26
	T-2	Trans.	357	360	3	31,000	1.26
800°F	T-6	Trans.	383	387	-	31,000	1.35
850°F	T-8	Trans.	375	378	-	24,000	1.32
900°F	T-10	Trans.	361	368	-	-	1.27
	T-11	Trans.	361	368	-	24,000	1.27
	T-12	Trans.	361	368	-	26,000	1.27
950°F	T-13	Trans.	351	365	1.0	36,000	1.23
	T-14	Trans.	351	365	1.0	31,000	1.23
	T-15	Trans.	351	365	1.0	33,000	1.23
1000°F	T-16	Trans.	312	332	2.0	47,000	1.10
	T-17	Trans.	312	332	2.0	41,000	1.10
	T-18	Trans.	312	332	2.0	49,000	1.10

TABLE 13

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PREPARED BY:	THE BUDD COMPANY PRODUCT DEVELOPMENT PHILADELPHIA, PA.	PAGE NO. OF
CHECKED BY:		REPORT NO.
DATE:	K_{C1} VS AGING TEMP. (3 HOURS)	PROJECT NO.

20% NI (HIGH TI MOD)
COLD ROLLED 65%
.032 GAGE

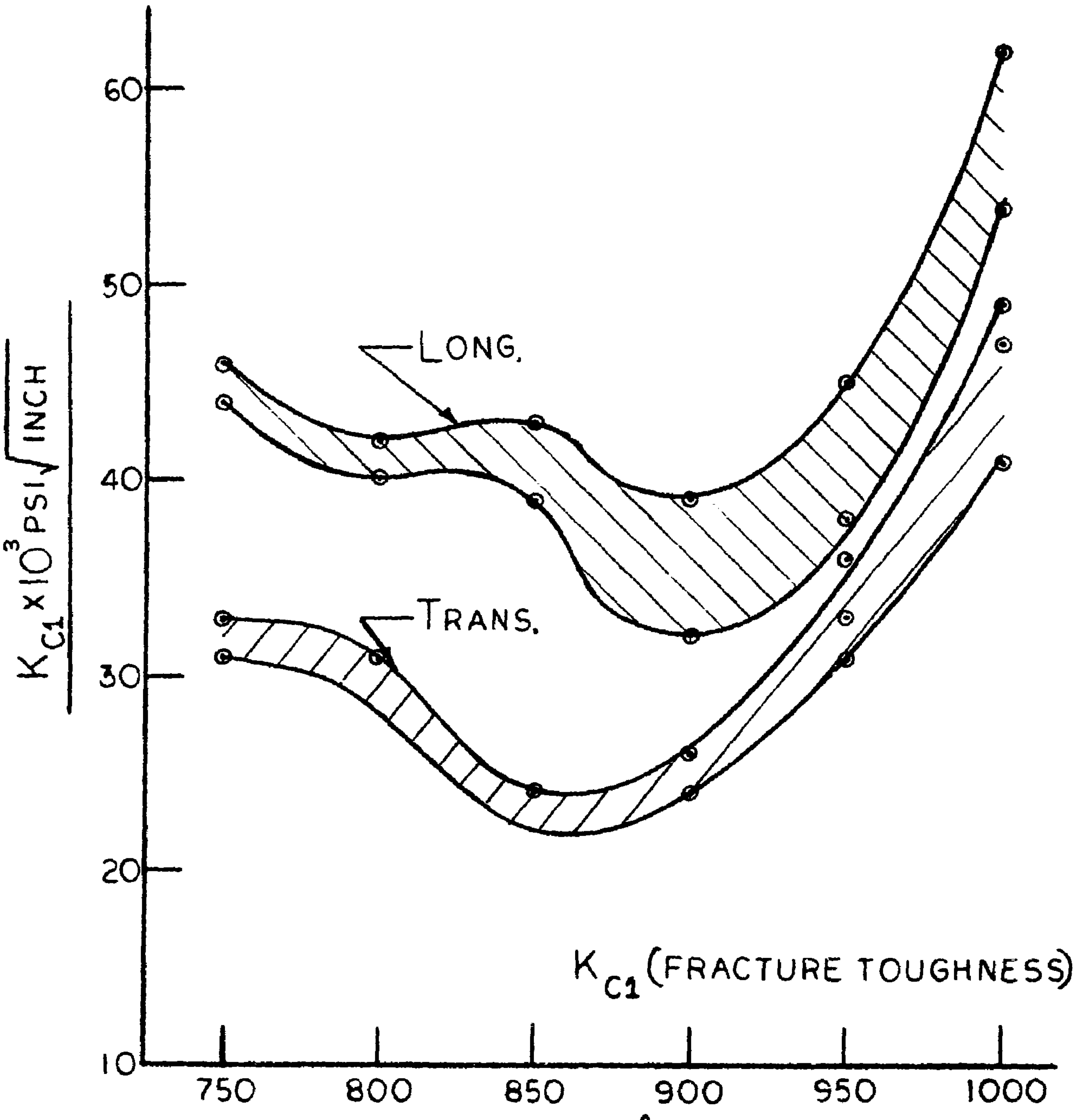

FIG. 3

The data show that when aged at 950°F for 3 hours, the longitudinal yield strength is at the level we expect to use for rocket motor case construction. Therefore, additional tests were made to evaluate the effects of time at this particular temperature. The results of this work are shown in the tensile data in Table 14, repeated graphically in Figure No. 4 and by the fracture energy values shown in Table 15 and in Figure No. 5.

With the limited test values it appears that the most favorable aging temperature is 950°F (or slightly higher) for material which has been cold reduced 65%. After aging at this temperature, the tensile yield strength is at the design level of between 305,000 and 315,000 psi, and the minimum toughness condition of both the longitudinal and transverse specimens is avoided.

Figure No. 4 shows that the maximum strength is reached after aging one hour or less, but in this condition the ductility and toughness are much reduced. The longer aging times of 3 and 4 hours reduces the strength but markedly improves the ductility and moderately improves the fracture toughness. During the

MECHANICAL PROPERTIES OF 20% NICKEL STEEL

HIGH Ti COMPOSITION

Heat No. 23579-1
0.032" Gage

Cold Rolled 65%
Sub-Zero Cooled and Aged 950°F for 1, 2 and 4 Hours

Aging Time (950°F)	No. of Tests	Direct.	Yield Strength 0.2% Offset KSI	Ult. Tensile Strength KSI	% El. in 2 Inches	Rockwell Hardness
1 Hour	2	Long.	338	346	2	RC 57-58
2 Hours	2	Long.	328	337	2	
4 Hours	2	Long.	311	323	2	
1 Hour	2	Trans.	367	377	-*	
2 Hours	3	Trans.	353	364	-*	
4 Hours	2	Trans.	338	352	1.5	

* Specimen broke outside of gage marks

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TABLE 14

PREPARED BY:	THE BUDD COMPANY PRODUCT DEVELOPMENT PHILADELPHIA, PA.	PAGE NO. OF
CHECKED BY:		REPORT NO.
DATE:	TENSILE STRENGTH VS. AGING TIME @ 950°F	PROJECT NO.

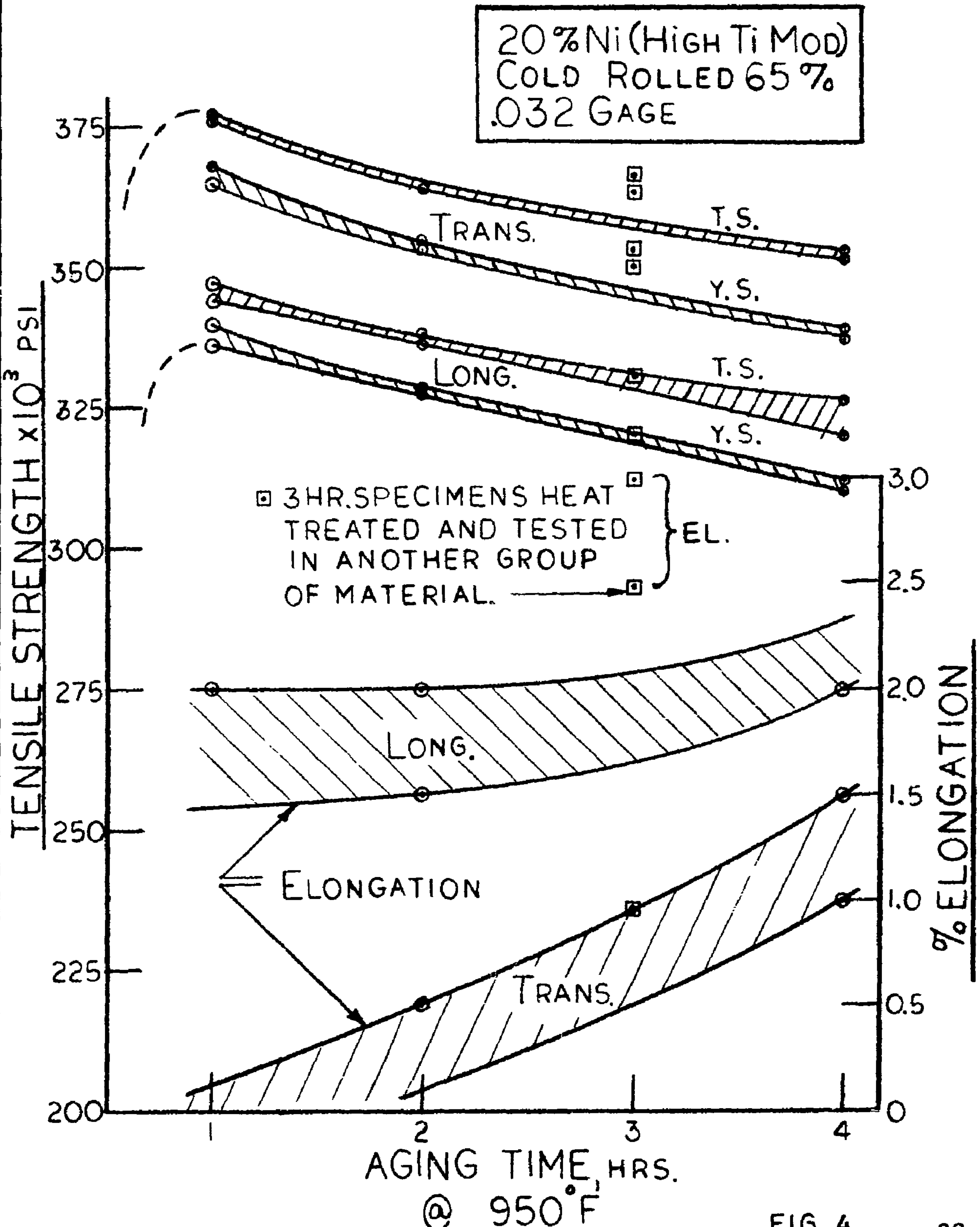

FIG. 4

FRACTURE ENERGY DATA OF 20% NICKEL STEEL
HIGH Ti COMPOSITION

Cold Rolled 65%
Sub-Zero Cooled and Aged at 950°F, for 1, 2, and 4 Hrs.

Heat No. 23579-1
0.032" Gage

Aging Time (950°F)	Spec. No.	Direct.	Yield Strength KSI $\sigma_{Y.S.}$	Ult. Strength KSI $\sigma_{Ult.}$	% El. in 2 Inches	K_{C1} PSI $\sqrt{\text{Inch}}$	$\frac{\sigma_{Y.S.}}{\text{density}}$ X 10^6
1 Hour	L-13	L	338	346	2	36,000	1.19
	L-14	L	338	346	2	37,000	1.19
2 Hours	L-15	L	328	337	2	37,000	1.16
	L-16	L	328	337	2	38,000	1.16
4 Hours	L-17	L	311	323	2	41,000	1.09
	L-18	L	311	323	2	43,000	1.09
1 Hour	T-19	T	367	377	-	29,000	1.29
	T-20	T	367	377	-	-	1.29
2 Hours	T-3	T	353	364	-	30,000	1.24
	T-21	T	353	364	-	30,000	1.24
	T-22	T	353	364	-	31,000	1.24
4 Hours	T-23	T	338	352	1.5	29,000	1.19
	T-24	T	338	352	1.5	31,000	1.19

TABLE 15

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PREPARED BY:	THE BUDD COMPANY PRODUCT DEVELOPMENT PHILADELPHIA, PA.	PAGE NO. OF
CHECKED BY:		REPORT NO.
DATE:	K_{C1} VS. AGING TIME @ 950°F	PROJECT NO.

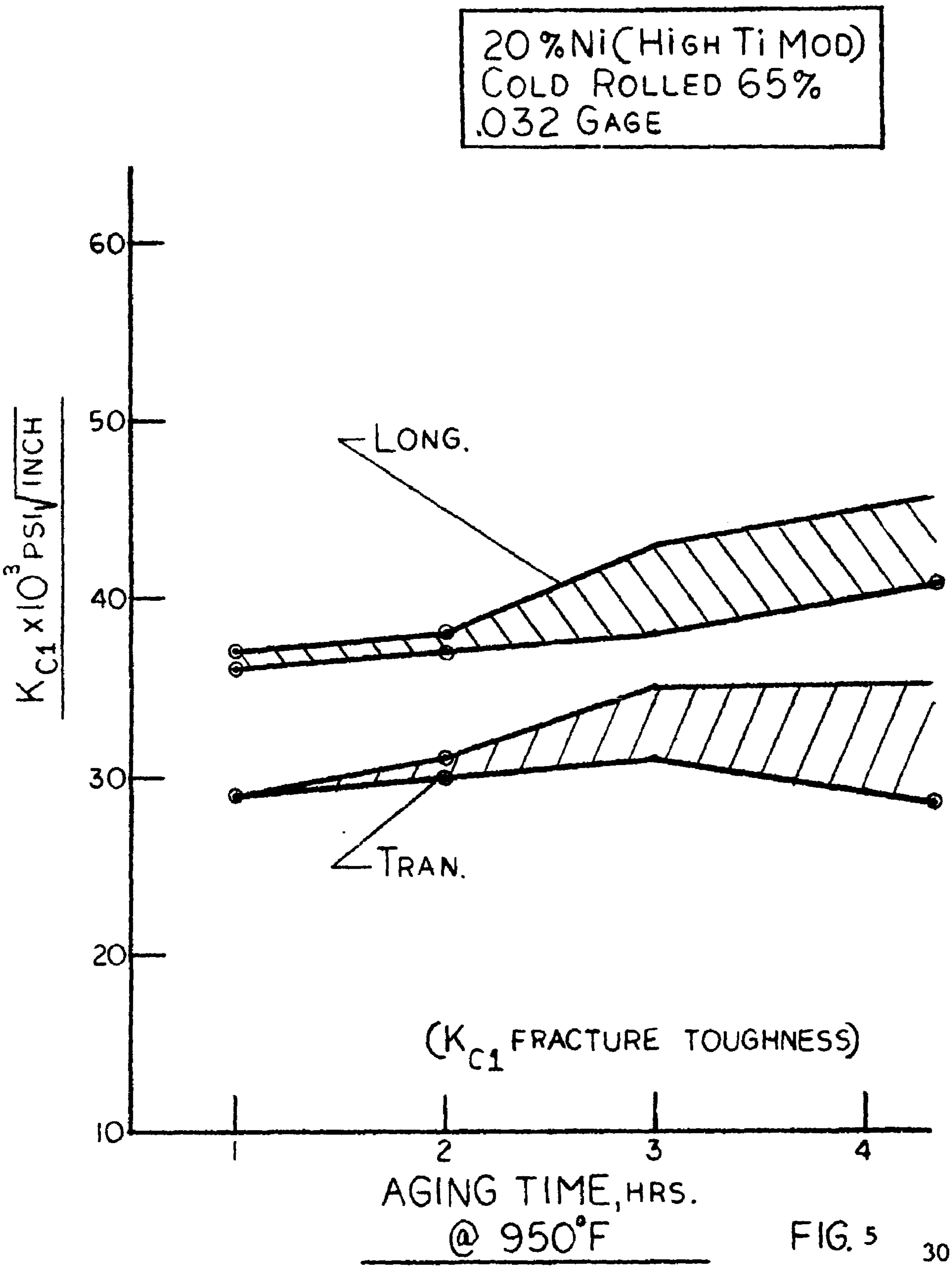

FIG. 5

next quarter we will investigate the effect of aging at longer times.

25% Nickel Steel - High Titanium Modification

The heat treating procedures for the modified 25% nickel steel were determined by the processing and testing of the 0.125 inch thick material. The two heat treatments that were initially used for tensile specimens only are as follows:

A - 1. Material in the 1500°F annealed condition.
 2. Aus-age at 1100°F, 16 hours; air cool.
 3. Cool at -100°F, 16 hours minimum; air warm.
 4. Mar-age at 800°F, 1 hour; air cool.

B - 1. Material in the 1500°F annealed condition.
 2. Aus-age at 1200°F, 8 hours; air cool.
 3. Cool at -100°F, 16 hours minimum; air warm.
 4. Mar-age at 800°F, 1 hour; air cool.
 5. Cool at -100°F, 16 hours minimum; air warm.
 6. Mar-age at 850°F, 1 hour; air cool.

The first treatment is similar to the double age used for "standard" analysis material. The second treatment uses a double sub-zero cool and age in an attempt to lessen the chance of retained austenite.

In previous work with material of the more "standard" analysis, difficulty was encountered in bringing about a complete transformation of the austenite to martensite. The properties of material mill annealed at 1500°F are shown in Table 16. The results of the above heat treatments are shown in Table 17.

The first heat treatment did not properly prepare the material for transformation. Very little martensite was formed after aus-aging at 1100°F for 16 hours. On the other hand, the 1200°F aus-age followed by a double sub-zero cool and double mar-age resulted in very high hardness and an embrittled condition. The tensile specimens from the second heat treatment fractured without showing any measurable yield point elongation.

The heat treatments were modified and new 0.125 inch thick specimens were prepared and tested. The adjusted heat treatments were as follows:

A - 1. Material in the 1500°F annealed condition.

2. Aus-age at 1200°F, 8 hours; air cool.

3. Cool at -100°F, 16 hours minimum; air warm.

4. Mar-age at 900°F, 2 hours; air cool.

MECHANICAL PROPERTIES OF 25% NICKEL STEEL

HIGH Ti COMPOSITION

Heat Number 23569-1
0.075" and 0.125" Gage

Mill Annealed
Average of Four Tests

Condition	Direct.	Yield Strength 0.2% Offset KSI	Ult. Tensile Strength KSI	% Elong. in 2 Inches	Rockwell Hardness
Annealed 0.075	Long.	84	118	36	RB 97
	Trans.	92	116	32	
Annealed 0.125	Long.	66	113	34	
	Trans.	83	113	31	

TABLE 16

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MECHANICAL PROPERTIES OF 25% NICKEL STEEL

HIGH Ti COMPOSITION

Heat Number 23569-1

0.125" Gage

Condition	Spec. No.	Direct.	Yield Strength 0.2% Offset KSI	Ult. Tensile Strength KSI	% Elong. in 2 Inches	Rockwell Hardness
1100°F, 16 Hrs.	GLAL-1	L	147	242	2	RC 50-51
-100°F, 16 Hrs.	GLAL-2	L	146	250	3.5	
800°F, 1 Hr.	GLAL-3	L	153	257	3	
	GLAL-4	L	144	243	3	
	GLAT-1	T	153	225	1	
	GLAT-2	T	153	249	2.5	
	GLAT-3	T	157	254	3	
	GLAT-4	T	150	240	1	
						RC 59-60
1200°F, 8 Hrs.	GSAL-1	L)	All specimens broke without reaching yield point. Very brittle fracture.			
-100°F, 16 Hrs.	GSAL-2	L)				
800°F, 1 Hr.	GSAL-3	L)				
-100°F, 16 Hrs.						
850°F, 1 Hr.	GSAT-1	T)				
	GSAT-2	T)				
	GSAT-3	T)				

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TABLE 17

B - 1. Anneal at 1600°F, 15 minutes; air cool.

2. Aus-age at 1150°F, 8 hours; air cool.

3. Cool at -100°F, 16 hours minimum; air warm.

4. Mar-age at 850°F, 2 hours; air cool.

The tensile properties obtained from these treatments are shown in Table 18. The high aus-aging temperature of 1200°F developed uniformly high strength despite the use of a higher mar-aging temperature.

The second treatment produced low strength, caused by the excess retention of austenite. Complete transformation may have been hampered by the 1600°F anneal or by the failure of the 1150°F aus-age to properly unstabilize the austenite in the 8 hours allowed.

The 0.075 inch sheet stock was then used in making tensile and fracture energy specimens. We expected that the previous heat treating work would indicate the most suitable schedules. The revised heat treatments for the 0.075 inch material are shown as follows:

MECHANICAL PROPERTIES OF 25% NICKEL STEEL

HIGH Ti COMPOSITION

Heat Number 23569-1

0.125" Gage

Condition	Spec. No.	Direct.	Yield Strength 0.2% Offset KSI	Ult. Tensile Strength KSI	% Elong. in 2 Inches	Rockwell Hardness
1200°F, 8 Hrs.	GLAL-5	L	291	346	-	RC 59-60
-100°F, 16 Hrs.	GLAL-6	L	294	352	2	
900°F, 2 Hrs.	GLAL-7	L	294	340	1.5	
	GLAL-8	L	292	340	2	
	GLAT-5	T	316	354	1.5	
	GLAT-6	T	306	356	1.5	
	GLAT-7	T	305	356	1.5	
	GLAT-8	T	307	356	2	
1600°F Anneal	GSAL-5	L	184	296	2.5	RC 56
1150°F, 8 Hrs.	GSAL-6	L	182	286	2	
-100°F, 16 Hrs.	GSAL-7	L	181	-	-	
850°F, 2 Hrs.						
	GSAT-5	T	194	296	2.5	
	GSAT-6	T	188	292	2.5	
	GSAT-7	T	190	286	-	

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TABLE 18

A - 1. Material in the 1500°F annealed condition.

2. Aus-age at 1200°F, 8 hours; air cool.

3. Cool at -100°, 16 hours minimum; air warm.

4. Mar-age at 900°F, 2 hours; air cool.

B - 1. Material in the 1500°F annealed condition.

2. Aus-age at 1200°F, 8 hours; air cool.

3. Cool at -100°F, 16 hours minimum; air warm.

4. Mar-age at 900°F, 2 hours; air cool.

5. Cool at -100°F, 16 hours minimum; air warm.

6. Mar-age at 950°F, 2 hours; air cool.

The tensile properties of the 0.075 inch material are shown in Table 19. The K_{C1} values, measuring the fracture toughness, of identically heat treated specimens are shown in Table 20.

Although the same heat treatments had developed satisfactory properties in the 0.125 inch material, the properties of the 0.075 inch specimens were much lower than had been anticipated. All the material is of the same heat and had been similarly mill processed. The double sub-zero cool and age improved the properties slightly but did not develop the strength capability of this composition. Again,

MECHANICAL PROPERTIES OF 25% NICKEL STEEL

HIGH Ti COMPOSITION

Heat Number 23569-1

0.075" Gage

Condition	Spec. No.	Direct.	Yield Strength 0.2% Offset KSI	Ult. Tensile Strength KSI	%Elong. in 2 Inches	Rockwell Hardness
1200°F, 8 Hrs.	GLAL-1	L	209	277	2.5	RC 58-60
-100°F, 16 Hrs.	GLAL-2	L	200	281	3.5	
900°F, 2 Hrs.	GLAL-3	L	212	290	-	
	GLAL-4	L	226	296	3	
	GLAT-1	T	-	301	-	
	GLAT-2	T	236	308	1.5	
	GLAT-3	T	232	321	3.5	
	GLAT-4	T	246	316	2	
1200°F, 8 Hrs.	GSAL-1	L	225	300	5.5*	RC-55-56
-100°F, 16 Hrs.	GSAL-2	L	224	300	11.5	
900°F, 2 Hrs.	GSAL-3	L	217	295	7.0*	
-100°F, 16Hrs.	GSAL-4	L	217	294	6.0*	
950°F, 2 Hrs.	GSAT-1	T	256	317	10	
	GSAT-2	T	244	316	4*	
	GSAT-3	T	239	320	9.5	
	GSAT-4	T	242	321	9	

*Specimen broke outside of gage marks

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TABLE 19

FRACTURE ENERGY DATA OF 25% NICKEL STEEL

HIGH Ti COMPOSITION

Heat Number 23569-1

0.075" Gage

Condition	Spec. No.	Direct.	Yield Strength KSI $\sigma_{Y.S.}$	Ult. Strength KSI $\sigma_{Ult.}$	% El. in 2 Inches	K_{C1} PSI $\sqrt{\text{Inch}}$	$\frac{\sigma_{Y.S.}}{\text{Density}}$ X 10^6
1200°F, 8 Hrs.	GLBL-3	L	215	286	3	24,000	0.75
-100°F,16 Hrs.	GLBL-4	L	215	286	3	22,000	0.75
900°F, 2 Hrs.							
	GLBT-1	T	238	312	2.5	23,000	0.84
	GLBT-2	T	238	312	2.5	24,000	0.84
	GLBT-3	T	238	312	2.5	22,000	0.84
	GLBT-4	T	238	312	2.5	23,000	0.84
1200°F, 8 Hrs.	GSBL-1	L	221	297	11.5	32,000	0.78
-100°F,16 Hrs.	GSBL-2	L	221	297	11.5	34,000	0.78
900°F, 2 Hrs.	GSBL-3	L	221	297	11.5	29,000	0.78
-100°F,16 Hrs.	GSBL-4	L	221	297	11.5	31,000	0.78
950°F, 2 Hrs.							
	GSBT-1	T	245	318	9.5	33,000	0.86
	GSBT-2	T	245	318	9.5	--	0.86
	GSBT-3	T	245	318	9.5	33,000	0.86
	GSBT-4	T	245	318	9.5	32,000	0.86

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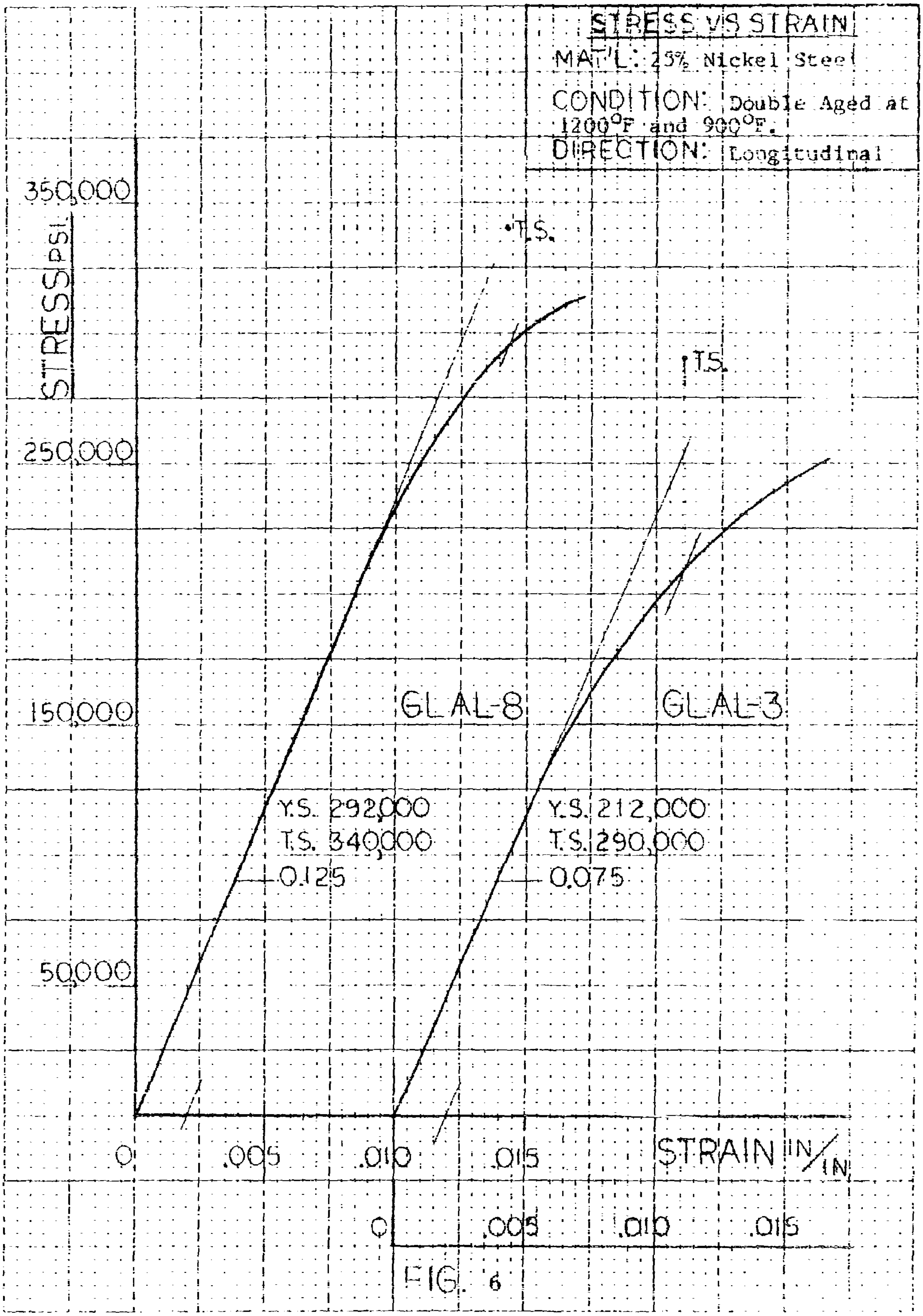
TABLE 20

this is a case of retained austenite as is evidenced by the large spread between the yield and ultimate tensile strengths. Also, the load-deformation diagrams shown on Figures Numbers 6 and 7, indicate the presence of austenite by the shape of the curves. The GLAL-8 and GLAT-8 specimens are properly transformed (see Table 18 for properties), whereas the GLAL-3 and GLAT-2 have a significant amount of austenite in the microstructure. This is indicated by the shape of the curve from the proportional limit to beyond the yield point. In this particular instance the indication is not very distinct.

Based on the work done to date, the most reliable heat treatment for this particular analysis of the 25% nickel steel would be as follows:

1. Material in the 1500°F annealed condition.
2. Aus-age at 1250°F, 8 hours; air cool.
3. Cool at -100°F, 16 hours minimum; air warm.
4. Mar-age at 900°F, 2 hours, air cool.

The 0.075 inch material was also purchased in the cold rolled condition. The strip had been 65% cold reduced by the mill and was shipped in the "as-rolled condition. Tensile and center notched fracture


STRESS VS STRAIN
MAT'L: 25% Nickel Steel
CONDITION: Double Aged at 1200°F and 900°F.
DIRECTION: Longitudinal
STRESS PSI
350,000
250,000
150,000
50,000
T.S.
T.S.
GL AL-8
GL AL-3
Y.S. 292,000
T.S. 340,000
0.125
Y.S. 212,000
T.S. 290,000
0.075
0
.005
.010
.015
STRAIN IN/IN
0
.005
.010
.015
FIG. 6

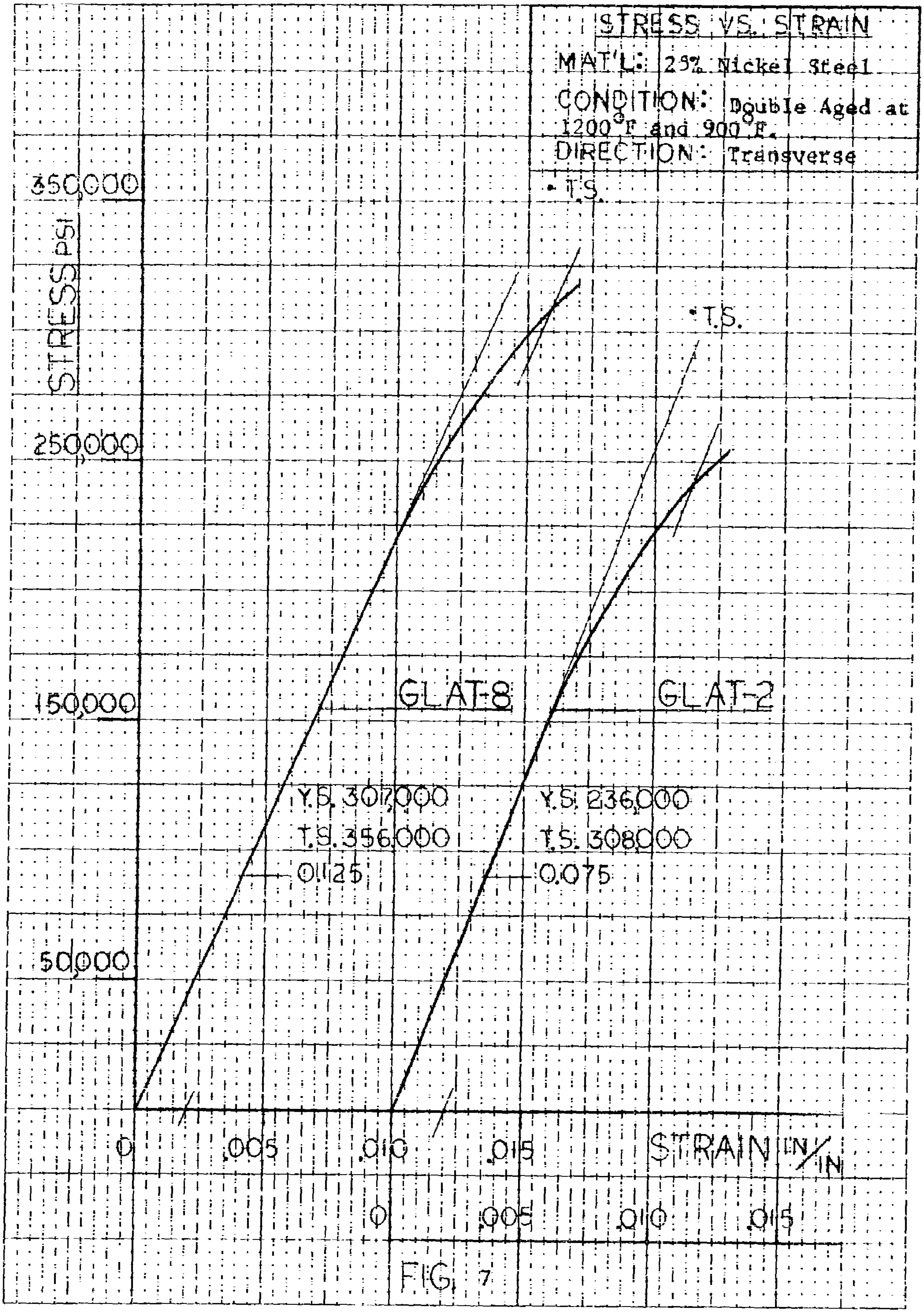

STRESS VS. STRAIN
MAT'L: 25% Nickel Steel
CONDITION: Double Aged at 1200°F and 900°F.
DIRECTION: Transverse
350,000
250,000
150,000
50,000
STRESS PSI
• T.S.
• T.S.
GLAT-8
GLAT-2
Y.S. 307,000
T.S. 356,000
Y.S. 236,000
T.S. 308,000
0.125
0.075
0
.005
.010
.015
STRAIN IN/IN
0
.005
.010
.015

FIG. 7

energy specimens were prepared, and after sub-zero cooling, were aged at 850°F for 3 hours. The cold rolled and aged tensile properties and fracture toughness are shown in Tables 21 and 22, respectively.

Experience has shown that cold reduction causes the metastable austenite to transform to martensite, and a gain in properties and hardness is realized. However, this alloy does not exhibit much work or strain hardening, and therefore, cold reduction in excess of what is needed for relatively complete transformation adds little to the strength. The sub-zero cool at -100°F is used to guarantee complete transformation in preparation for final maraging.

The tensile properties of the cold rolled and aged 25% nickel steel are considerably lower than the similarly treated 20% nickel alloy. This is attributed to the fact that the 20% nickel steel is martensitic as annealed and the cold reduction work hardens the martensite. The entire 65% reduction is used in this effort, whereas with the 25% nickel grade part of the reduction is consumed in inducing transformation, with the remainder used to strain harden

MECHANICAL PROPERTIES OF 25% NICKEL STEEL

HIGH Ti COMPOSITION

Heat Number 23569-1
0.075" Gage

Cold Rolled 65%
Sub-zero Cooled and Aged at 850°F, 3 hours

Condition	Spec. No.	Direct.	Yield Strength 0.2% Offset KSI	Ult. Tensile Strength KSI	% Elong. in 2 Inches	Rockwell Hardness
Cold Rolled,	GNAL-1	L	275	305	2	RC 57-59
-100°F, 16 Hrs.	GNAL-2	L	264	304	3	
850°F, 3 Hrs.	GNAL-3	L	287	307	3.5	
	GNAL-4	L	278	297	4	
	GNAT-1	T	295	315	1	
	GNAT-2	T	311	335	1	
	GNAT-3	T	308	333	2	
	GNAT-4	T	305	333	.5	

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TABLE 21

FRACTURE ENERGY DATA OF 25% NICKEL STEEL
HIGH Ti COMPOSITION

Heat Number 23569-1
0.075" Gage

Cold Rolled 65%
Sub-Zero Cooled and Aged at 850°F, 3 Hrs.

Condition	Spec. No.	Direct.	Yield Strength KSI $\sigma_{Y.S.}$	Ult. Tensile KSI $\sigma_{Ult.}$	% El. in 2 Inches	K_{C1} PSI$\sqrt{\text{inch}}$	$\frac{\sigma_{Y.S.}}{\text{Density}}$ X 10^6
Cold Rolled	GNBL-1	L	281	303	3	53,000	0.99
-100°F,	GNBL-2	L	281	303	3	55,000	0.99
16 Hrs.	GNBL-3	L	281	303	3	49,000	0.99
850°F, 3 Hrs.	GNBL-4	L	281	303	3	48,000	0.99

No transverse test data.

TABLE 22

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the martensite.

No additional testing was done with the 25% nickel material. In the interim we had made a decision to concentrate our efforts on the evaluation of the 20% nickel steel. Therefore, although limited work with the 25% alloy leaves a number of unanswered questions, we do not intend to do any additional testing at this time.

JLS 300 Fracture Toughness

The fracture toughness data on the cold rolled JLS 300 alloy were inadvertently omitted when the results of the testing of that alloy were published. These values are shown in this report in Table 23. The fracture toughness, as indicated by K_{Cl} values, is exceptionally high in the longitudinal direction for material at a 344,000 psi yield strength. The toughness of the lower strength transverse direction is less. However, these values are reasonably high, as compared with other alloys at an equivalent strength level.

In a design where low strength annealed welds could be tolerated, the JLS 300 stainless steel could prove highly desirable. The weld nugget and heat affected zones develop properties similar to annealed Type 301 stainless steel. In our present rocket motor case design we require welds which possess yield strengths equal to from 60 to 75% of the base metal yield strength. For this reason, the JLS 300 alloy was not selected for further consideration.

FRACTURE ENERGY PROPERTIES OF JLS 300
STAINLESS STEEL

Cold Rolled and Aged
10" Wide Coil

Heat No. 61616
0.040" Gage

Spec. No.	Direct.	Yield Strength KSI $\sigma_{Y.S.}$	Ult. Strength KSI $\sigma_{Ult.}$	%El. in 2 Inches	K_{Cl} PSI $\sqrt{\text{inch}}$	$\frac{\sigma_{Y.S.}}{d} \times 10^6$
FNBL-1	L	344	346	2	101,000	1.21
FNBL-2	L	344	346	2	129,000	1.21
FNBL-3	L	344	346	2	111,000	1.21
FNBL-4	L	344	346	2	116,000	1.21
FNBT-1	T	330	341	2.5	56,000	1.16
FNBT-2	T	330	341	2.5	59,000	1.16
FNBT-3	T	330	341	2.5	54,000	1.16
FNBT-4	T	330	341	2.5	53,000	1.16
FNBL-2X*	L	344	345	2	106,000	1.21
FNBL-4X*	L	344	345	2	110,000	1.21

*6" Wide Coil

The Budd Co.
1-62

TABLE 23

WELDING OF 20% NICKEL STEEL

An extensive study has been initiated to evaluate the welding characteristics of the high Ti modification of the 20% nickel alloy. Tungsten inert gas (TIG) arc welding has been used to weld material in the following conditions:

0.032 inch . . . . cold rolled 65%

0.032 inch . . . . cold rolled and aged

0.075 inch . . . . annealed

0.075 inch . . . . annealed and aged

Tensile testing will be done with specimens in the "as-welded" condition and in various post welding heat treated conditions. The specimen will be made with the weld perpendicular to the direction of tensile loading. This specimen, similar to the base metal tensile specimen, is shown in drawing No. 2434-0003, previously published in Report No. 6, issued in January, 1961. In addition, we plan to design and use center notched specimens to measure the fracture toughness of various regions of the weld zone.

Automatic welding has been done using 6 inch X 13 inch test sections with the weld along the long edge. A square-edge butt joint was used with both the 0.032 inch and 0.075 inch material. The cold rolled material was

degreased with acetone before welding. The area to be welded of the annealed and aged material was wire brushed to remove the oxidized surface. This was followed by polishing with 120 grit and 400 grit emery papers. The surfaces were finally cleaned with acetone.

At this time we have only used a matching analysis filler wire. We expect delivery of two modified compositions in early February. The modified types will have lower percentages of the hardening elements, Ti and Al. In addition, one type will contain 1.5% Mo. The International Nickel Company has also promised to send us a small quantity of the 18% nickel, 8% cobalt, 5% molybdenum wire for our evaluation.

The welding schedules found to be optimum for the 0.032 inch and 0.075 inch material are shown in Figure No. 8. When this material is welded in other conditions and gages, the changes, if any, in the basic schedules will be reported.

The arc welding study has shown that the variables which are most important are heat input, restraint, and shielding. The thermal conditions, produced by weld current and location of chill bars is critical, with weld bead

TIG WELDING SCHEDULES

MAT'L: 20% NICKEL STEEL - HIGH TITANIUM COMPOSITION

Gage	Material Condition	Weld Current, Amps.	Arc Voltage, Volts	Travel Speed In./min.	Wire Diam. Ins.	Wire Feed, In./min.	Electrode Dia., Ins.	Chill Bar Spacing, Ins.
0.032"	Cold Rolled	48-54	8-9	10	1/32	12	1/16	1/4
0.075"	Annealed	100-105	10	8½	1/32	18	3/32	1/2

Welding Conditions Common to Both Material Conditions and Gages

1. Weld current is direct current, straight polarity (DCSP)
2. Matching analysis filler wire
3. Back-up plate (dwg. no. 2434-0103), groove 0.050" X 0.250", with gas ports
4. Metallic nozzle I.D. - 5/8" (#10)
5. 2% thoriated tungsten electrodes dressed to a conical point
6. Electrode stick out - 1/2"
7. Copper chill bars
8. Torch gas - argon at 30 CFH, trail gas - argon at 15 CFH, back-up gas - helium at 12 CFH.

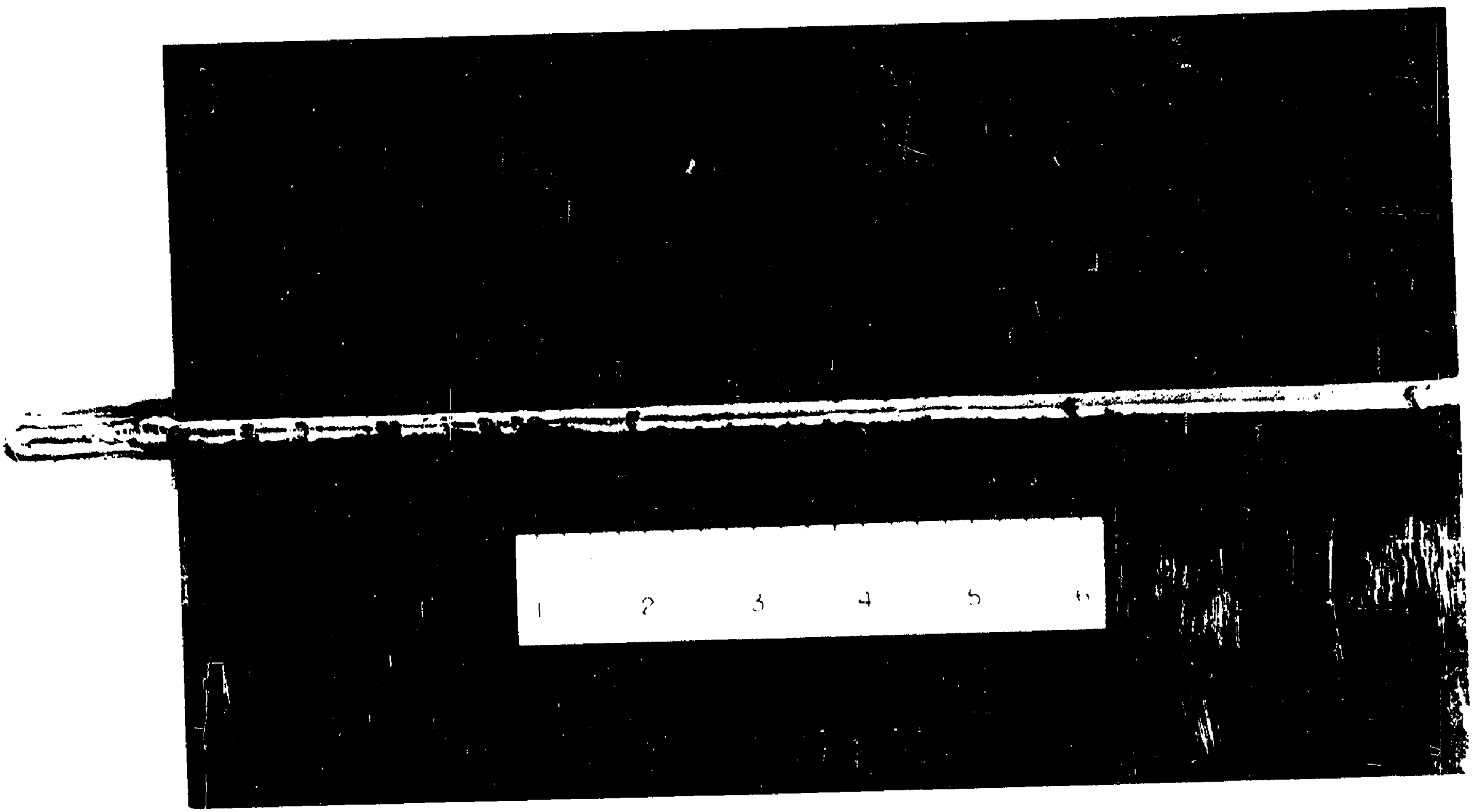
The Budd Co.
1-62

FIGURE NO. 8

cracking occurring if the heat is too high and the chilling too drastic. This was overcome by careful selection of welding current, widening of the backup groove, and wide spacing of the copper hold-down bars. It was also found that rigid restraint made the weld more sensitive to center-line cracking.

Adequate shielding with argon or helium is most important because of the high titanium and aluminum content of the alloy. Figure No. 9 is a photograph of a weld in the 0.032 inch material which shows the presence of oxide patches on the surface of the weld. With an extremely careful setup to insure the elimination of air from the surface of the molten metal, we have produced welds with less oxide than is shown on this sample. A trail cup is essential, in the welding of this material, to minimize the oxidation of the semi-molten and solidifying deposit.

Dye-penetrant and radiographic inspection showed the final welds to be free from internal defects. Gas porosity was not seen in any of the radiographs. Scattered tungsten inclusions of very small size were the only defects. Crater cracks were found at the end of the welds, but these were removed from the test section.



TUNGSTEN INERT GAS ARC WELD

20% Nickel Steel 0.032" Gage

Figure No. 9

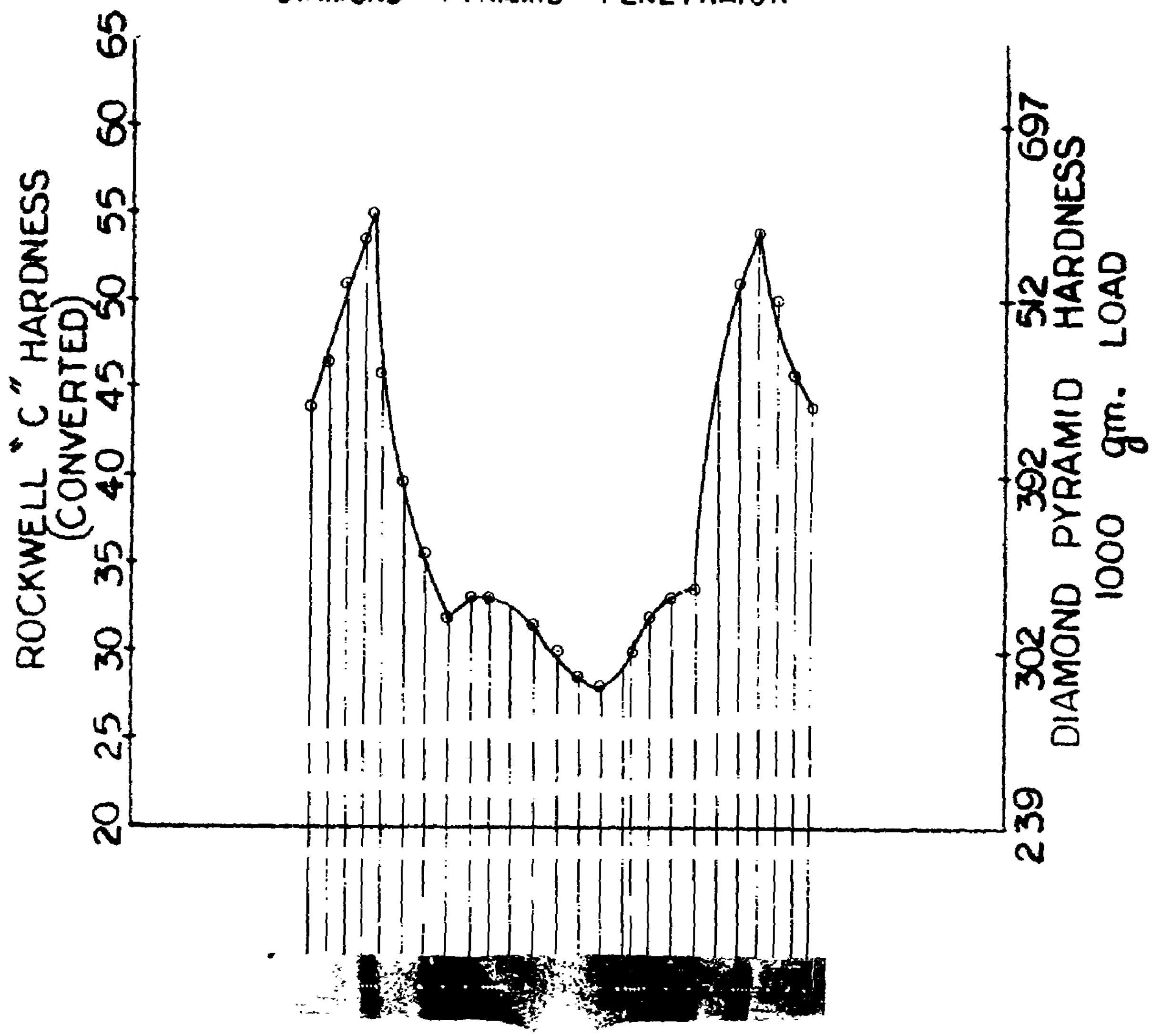
The microhardness variation across the weld zone of 0.075 inch thick annealed and welded material is shown in Figure No. 10. Figure No. 11 shows the microhardness traverse after sub-zero cooling and aging at 950°F following the welding. It is significant to note that the vast differences in hardness in the annealed and welded condition are largely eliminated after the moderate heat treatment. A complete survey of the relationships of pre-weld and post-weld treatments, and the effect of these treatments on microstructure and tensile properties is now being made. This work will be fully discussed in the next quarterly report.

20 INCH DIAMETER TEST CHAMBERS

Design drawings have been prepared for the 20 inch diameter test chambers. Figure No. 12, drawing B2434-0169, shows the design employing 20% nickel steel, and having one elliptical head and one flat test plate. Figure No. 13, drawing B2434-0165, shows the design using Ti 13V-11Cr-3Al alloy and having one elliptical head and one flat test plate. The elliptical heads will be over-strength with the cylindrical section tapered to match the chamber cylinder thickness. Since the primary purpose of these first tests

MICRO HARDNESS TRAVERSE

WELD CROSS SECTION
KENTRON MICRO HARDNESS TESTER
DIAMOND PYRAMID PENETRATOR



SPEC. NO. HAO WELD TYPE TIG MAG. 5X
ETCHANT 5% Ferric Chloride

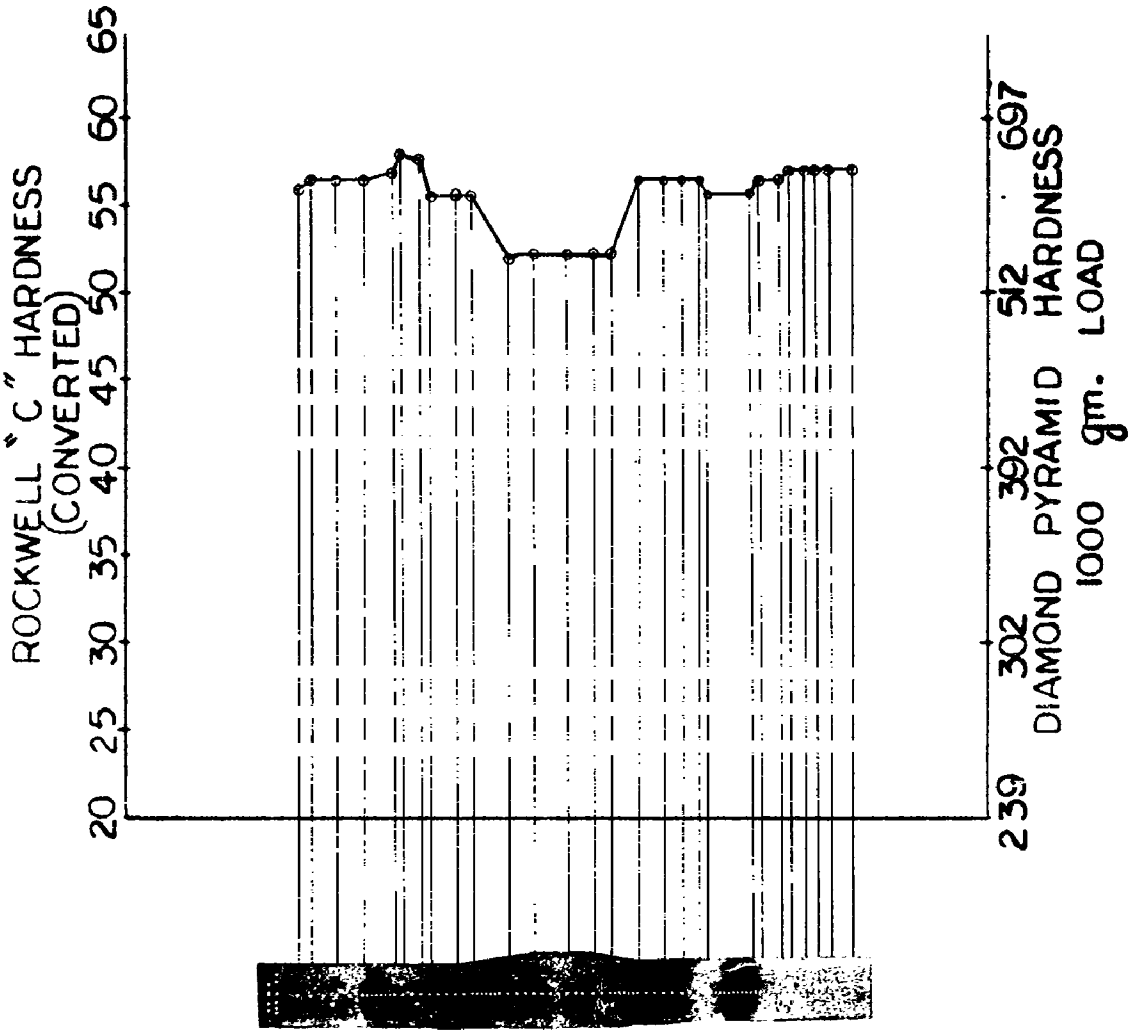
MATERIAL 20% Ni Steel (High Ti Grade), 0.075"
CONDITION Annealed and welded.

WELD SIZE WIDTH: 0.220" Top, 0.140" Bottom

FIG. 10

MICRO HARDNESS TRAVERSE

WELD CROSS SECTION
KENTRON MICRO HARDNESS TESTER
DIAMOND PYRAMID PENETRATOR

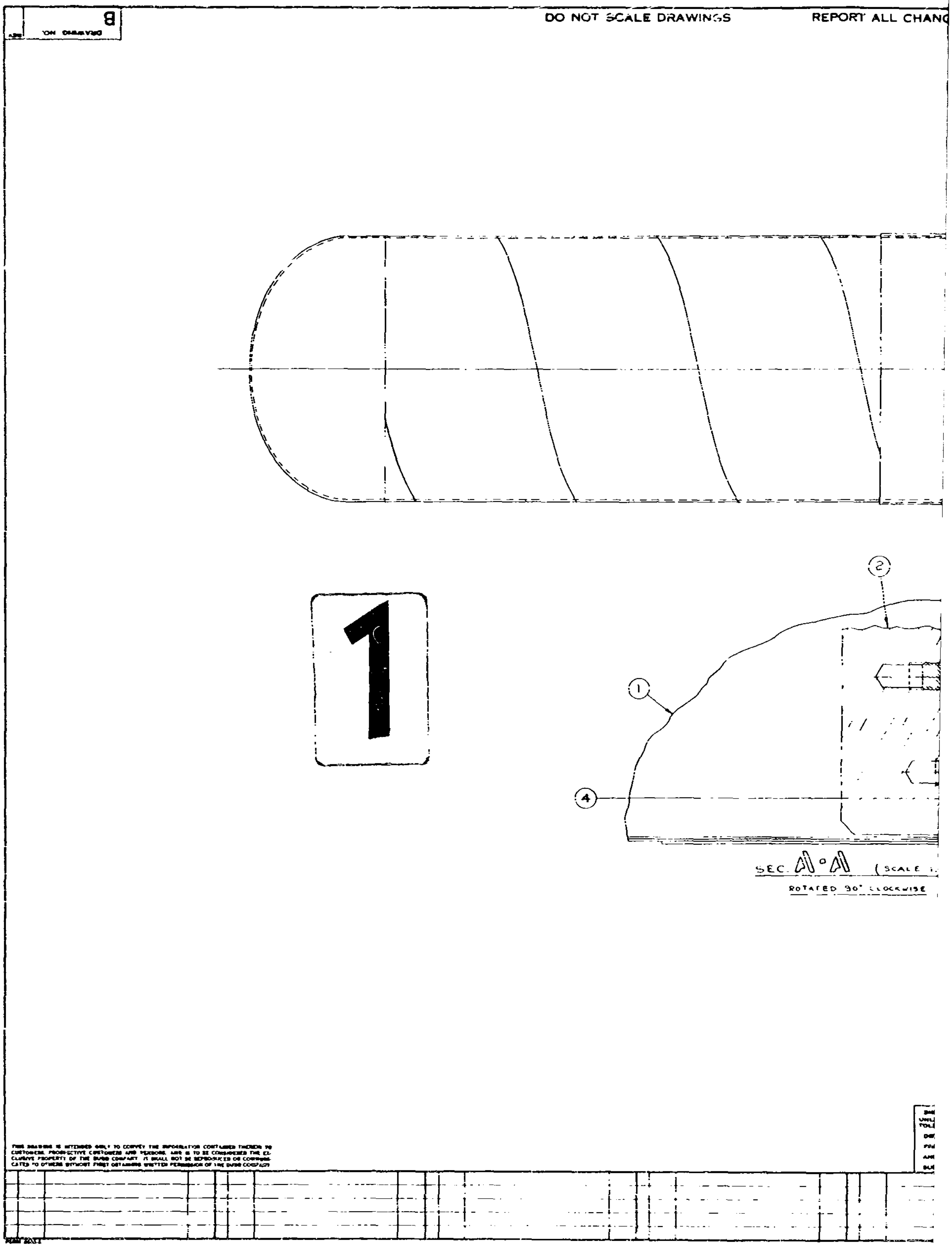


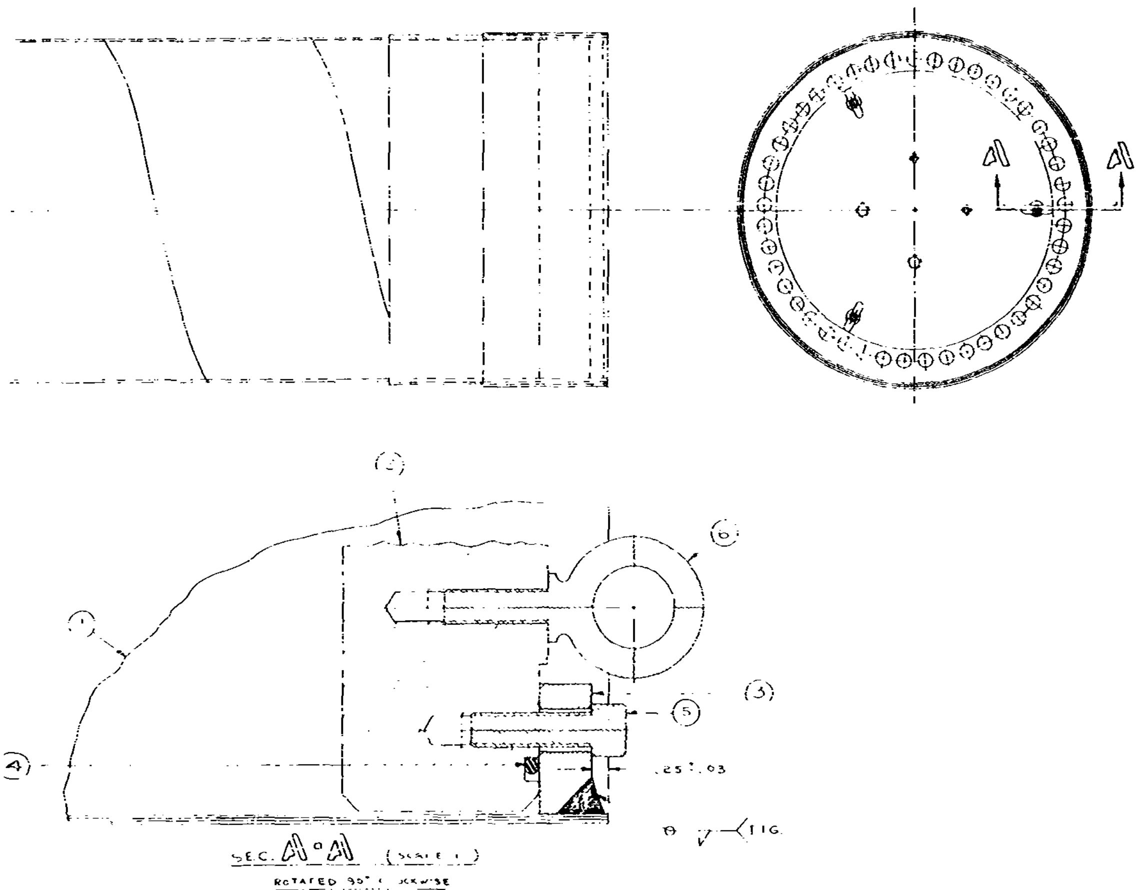
SPEC. NO. HLO WELD TYPE TIG MAG. 5X
ETCHANT 5% Ferric Chloride

MATERIAL 20% Ni Steel (High Ti Grade), 0.075"
CONDITION Annealed, welded, aged 950°F for 3 hours.

WELD SIZE WIDTH: 0.220" Top, 0.160" Bottom

FIG. 11


DO NOT SCALE DRAWINGS
REPORT ALL CHANG
1
2
1
4
SEC. A-A
ROTATED 90° CLOCKWISE



2

FIGURE 12

Piece No.	Qty	Description	Material	Mtl's Spec.	Item	Rev.
	3	EYEBOLT ARMSTRONG #28 OR EQUIV. 1/2-13 UNC			6	
	45	SOCK. HD. CAP SCREW "VIBRADI" 1/2-13 UNC X 1 1/2 LONG			5	
F2434-0126	1	"O" RING			4	
D2434-0130	1	RING - TEST RETAINING			3	
D2434-0125	1	TEST PLATE			2	
B2434-0168	1	HEAD, SHELL, & COUPLER ASSY.			1	
B2434-0165	1	TEST ASSY.				

DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED TOLERANCES ARE AS FOLLOWS:
DECIMAL
FRACTION
ANGLES
SURF. FIN.

USED ON | JOB | PIECE NO | QTY

RELEASE FOR EXPERIMENTAL ORDER

THE BUDD COMPANY
PRODUCT DEVELOPMENT
PHILADELPHIA 32, PA.

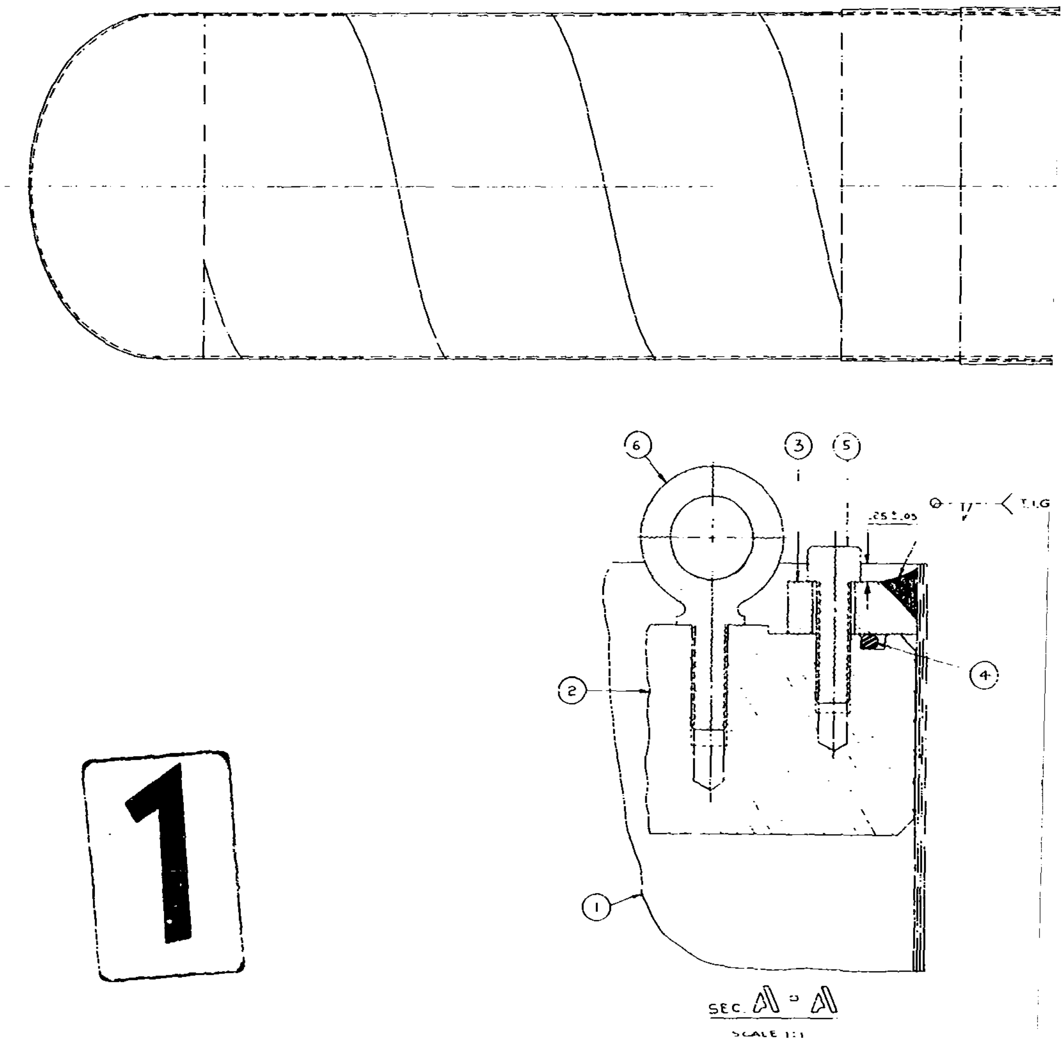
TITLE: 20" DIA. CHAMBER TEST UNIT 20 % NICKEL STEEL

DRAWING NO. B 2434-0169 REV. A

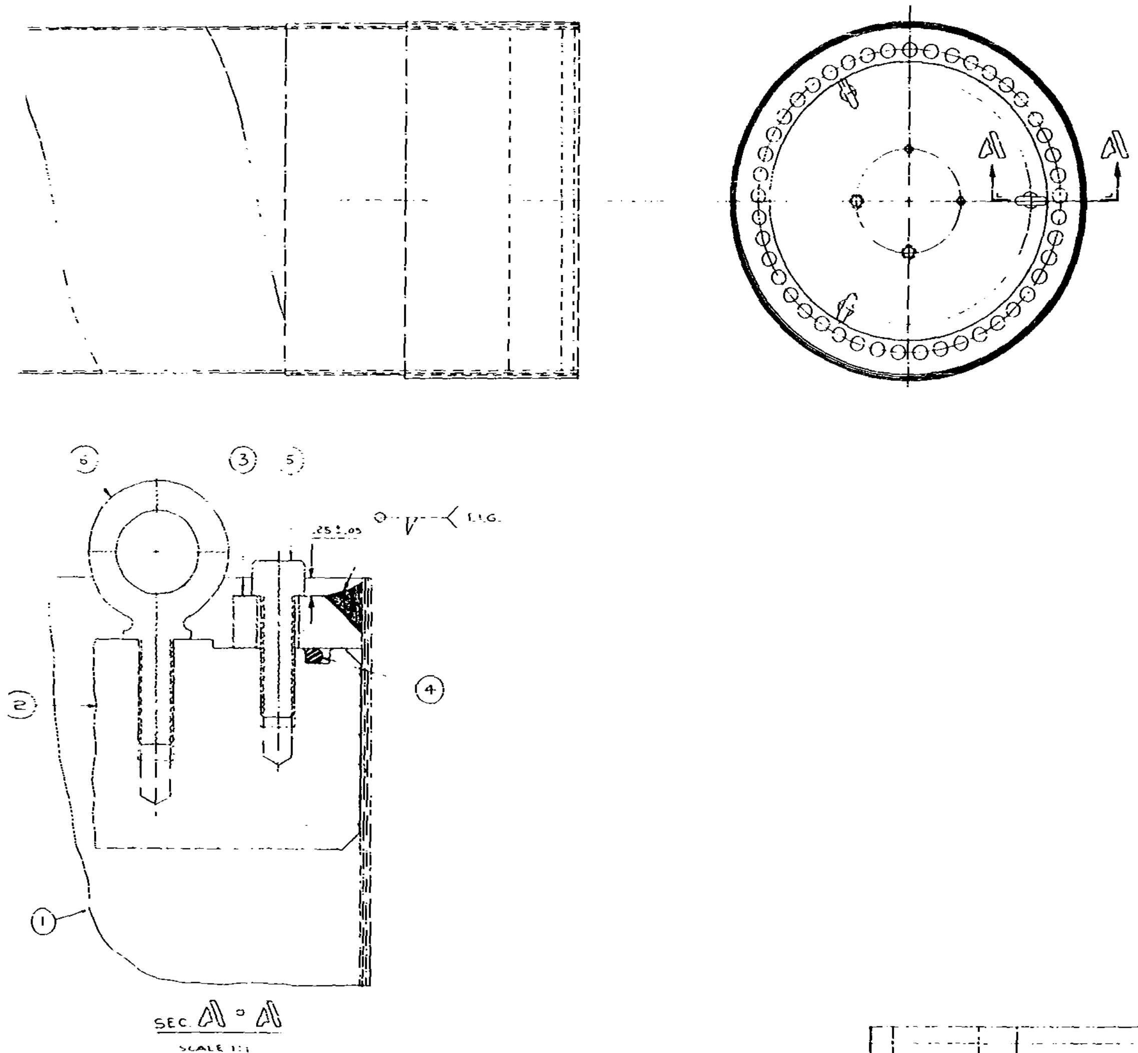
DRAWN: a/b CHECKED APPROVED STRESS APPROVED MTL'S APPROVED WELDING APPROVED APPROVED SCALE 1:4

DRAWING NO. B

DO NOT SCALE DRAWINGS REPORT ALL CHANGES AN



DIMENSIONS
UNLESS OTHE
TOLERANCES
DECIMAL
FRACTION
ANGLES
SURF FIN



2

FIGURE 13

PIECE NO.	QTY.	DESCRIPTION	MATERIAL	MTL'S. SPECS.	ITEM	REV.
	3	EYEBOLT "ARMSTRONG" #251 OR EQUIV. $\frac{1}{2}$-13 UNC			6	
	45	SOCK. HD. CAP SCREW "UNBRAKO" $\frac{1}{2}$-13 UNC X 1$\frac{3}{4}$ LONG			5	
F2434-0126	1	"O" RING			4	
D2434-0164	1	RING - TEST RETAINING			3	
D2434-0129	1	TEST PLATE			2	
B2434-0156	1	HEAD, SHELL, & DOUBLER ASSY.			1	
B2434-0165	1	TEST ASSY.				

DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED TOLERANCES ARE AS FOLLOWS
DECIMAL
FRACTION
ANGLES
SURF. FIN.

USED ON | JOB | PIECE NO. | QTY

A | RELEASE FOR EXPERIMENTAL ORDER

THE BUDD COMPANY
PRODUCT DEVELOPMENT
PHILADELPHIA 32 PA.

TITLE: 20" DIA. CHAMBER TEST UNIT Ti-13VA.-11CR.-3AL. ALLOY

DRAWING NO. B2434-0165 REV. A

DRAWN: 27 NOV 61 | CHECKED | APPROVED STRESS | APPROVED MTLS | APPROVED WELDING | APPROVED | APPROVED | SCALE 1:1

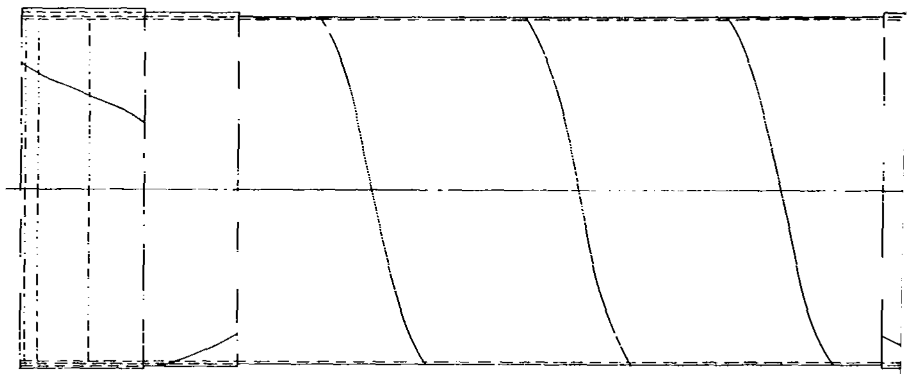
is to prove the cylinder design concept, we are providing, as a backup, an alternate 20 inch test unit in the event of a serious delay in the procurement of elliptical heads. Figure No. 14, drawing B2434-0207, shows the flat end test for 20% nickel chambers and Figure No. 15, drawing B2434-0208, is the design for the Ti 13V-11Cr-3Al chambers.

Strip materials on order for the 20 inch diameter test chambers have been delayed in shipment due to difficulties encountered during processing at the mill. The Ti 13V-11Cr-3Al alloy ordered from Titanium Metals Corporation is presently expected in late January, 1962. The 20% nickel steel on order with Allegheny-Ludlum is expected by mid February, 1962.

The helical butt welding of the cylindrical section will be accomplished in a specially designed fixture. Figure No. 16 is a photograph of this fixture. The tryout of this fixture was basically complete during the quarter using the T.I.G. welding process. Figure No. 17 is a photograph of a 20 inch diameter AM355 steel cylinder made during tryout in which eleven inch wide strip was used. Continued work with the selected 20% nickel and Ti 13V-11Cr-3Al alloys will be done upon receipt of these materials from the mills.

DRAWING NO. B REV

DO NOT SCALE DRAWINGS REPORT ALL C



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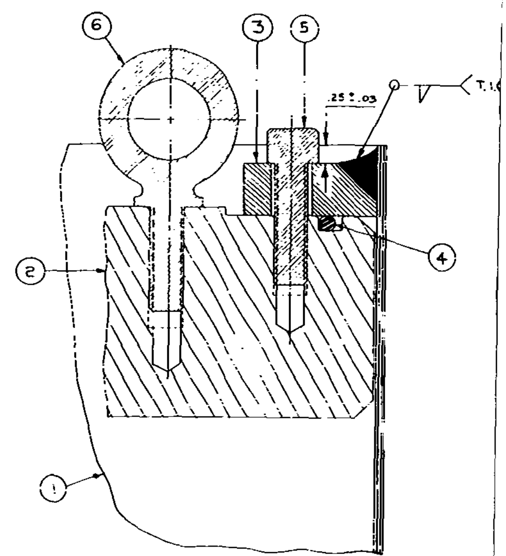
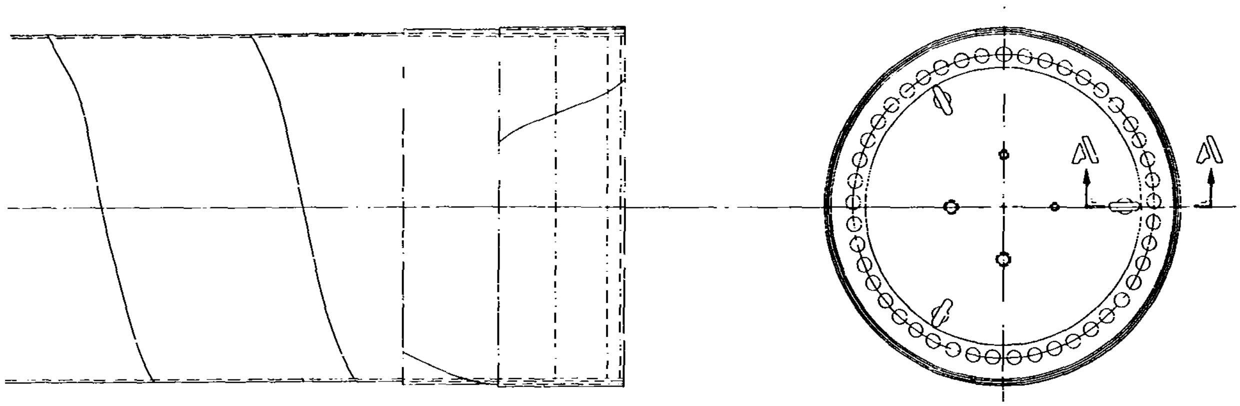
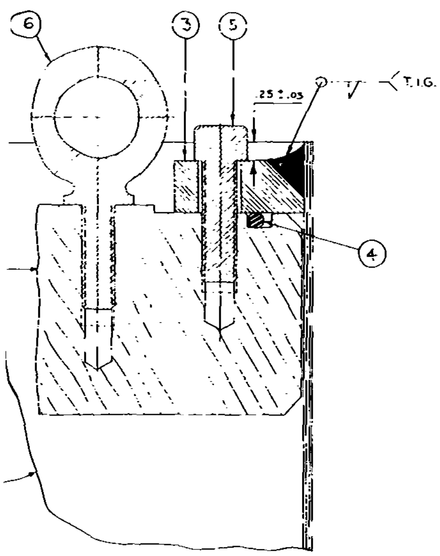


SEC. A - A

TYPICAL BOTH ENDS EXCEPT EYEBOLTS (ITEM 6) IN ONE END ONLY.

(SCALE 1:1)





SEC. A - A

TYPICAL BOTH ENDS EXCEPT EYEBOLTS (ITEM 6) IN ONE END ONLY.

(SCALE 1:1)

FIGURE 14

PIECE NO.	QTY.	DESCRIPTION	MATERIAL	MTL'S. SPECS.	ITEM	REV.
	3	EYEBOLT "ARMSTRONG" #25	OR EQUIV. ½-13 UNC		6	
	90	SOCK. HD. CAP SCREW "UNBRAKO"	½-13 UNC X 1¾ LONG		5	
F2434-0128	2	"O" RING			4	
D2434-0130	2	RING-TEST RETAINING			3	
D2434-0129	2	TEST PLATE			2	
B2434-0208	1	SHELL & DOUBLER ASSY			1	
B2434-0207	1	TEST ASSY.				

DIMENSIONS ARE IN INCHES. UNLESS OTHERWISE SPECIFIED TOLERANCES ARE AS FOLLOWS: DECIMAL FRACTION ANGLES SURF. FIN.

USED ON | JOB: 8601-255-2434 | PIECE NO. | QTY.

THE BUDD COMPANY
PRODUCT DEVELOPMENT
PHILADELPHIA 32, PA.

TITLE: 20" DIA. FLAT ENDS CHAMBER-TEST UNIT 80% NICKEL

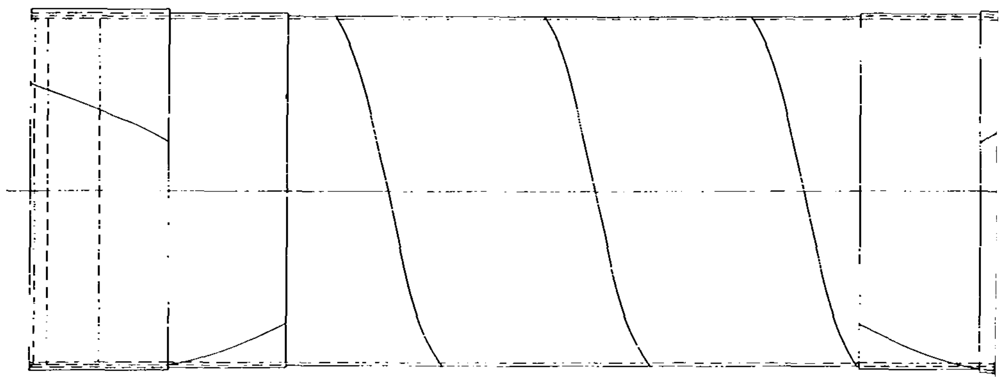
DRAWING NO. B2434-0207 REV. A

DRAWN: afB 14 DEC. '61 | CHECKED | APPROVED-STRESS | APPROVED-MTLS. | APPROVED-WELDING | APPROVED | APPROVED | SCALE 1:4

A REL. FOR EXPER. ORDER

2

DO NOT SCALE DRAWINGS REPORT ALL CHANG



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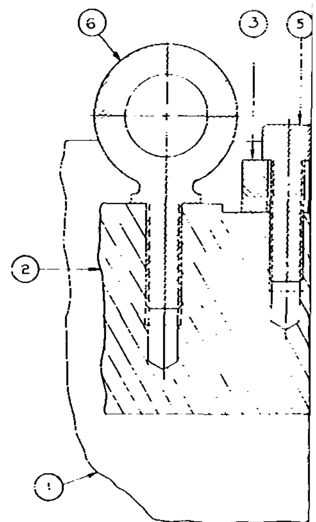
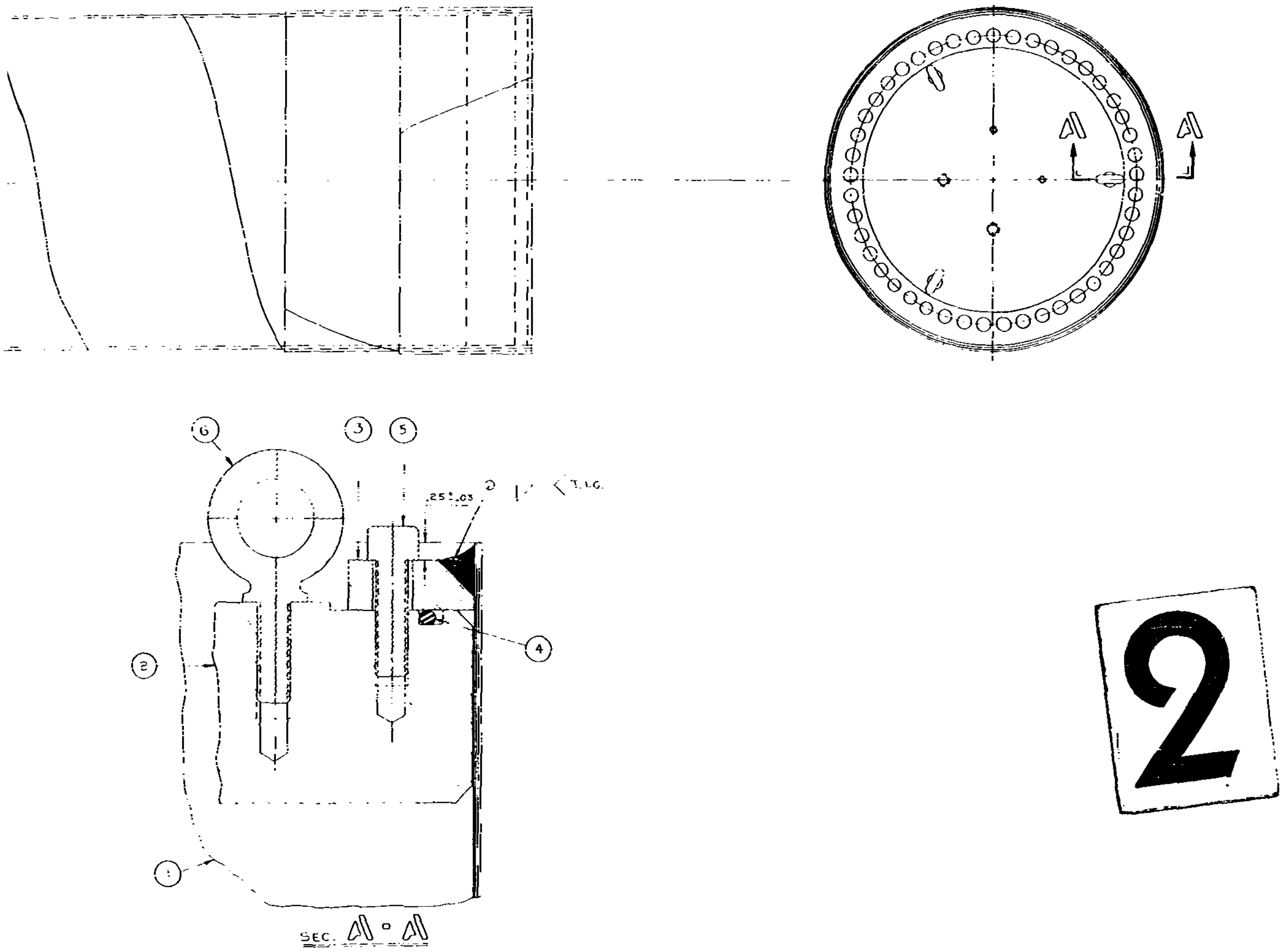


SEC. A - A

TYPICAL BOTH ENDS EXCEPT EYEBO
IN ONE END ONLY.

(SCALE 1:1)



SEC. A - A

TYPICAL BOTH ENDS EXCEPT EYEBOLTS (ITEM 6) IN ONE END ONLY.

(SCALE 1:1)

FIGURE 15

PIECE NO.	QTY.	DESCRIPTION	MATERIAL	MTL'S. SPECS.	ITEM	REV.
	3	EYEBOLT "ARMSTRONG" #25 OR	EQUIV. $\frac{1}{2}$-13 UNC		6	
	90	SOCK. HD. CAP SCREW "UNBRAKO"	$\frac{1}{2}$-13 UNC X 1$\frac{3}{4}$ LONG		5	
F2434-0126	2	"O" RING			4	
D2434-0164	2	RING - TEST RETAINING			3	
D2434-0165	1	TEST PLATE			2	
B2434-0206	1	SHELL & DOUBLER ASSY			1	
B2434-0208	1	TEST ASSY				

DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED TOLERANCES ARE AS FOLLOWS:
DECIMAL
FRACTION
ANGLES
SURF. FIN.

USED ON | JOB | PIECE NO. | QTY.

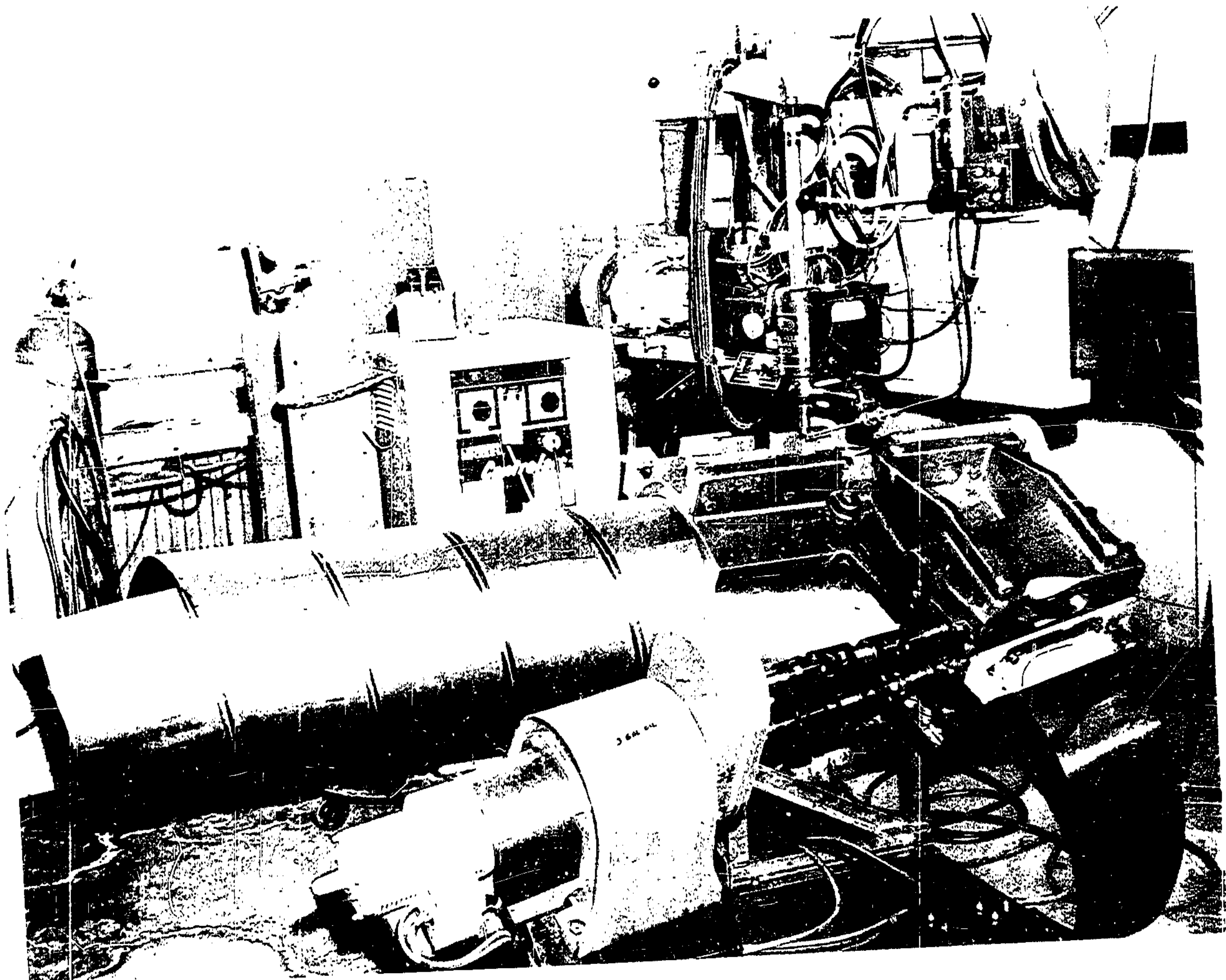
THE BUDD COMPANY
PRODUCT DEVELOPMENT
PHILADELPHIA 32 PA.

TITLE: 20" DIA. FLAT ENDS CHAMBER - TEST UNIT TI - 13V - 11CR. - 3 AL. ALLOY

DRAWING NO. B2434-0208 REV. A

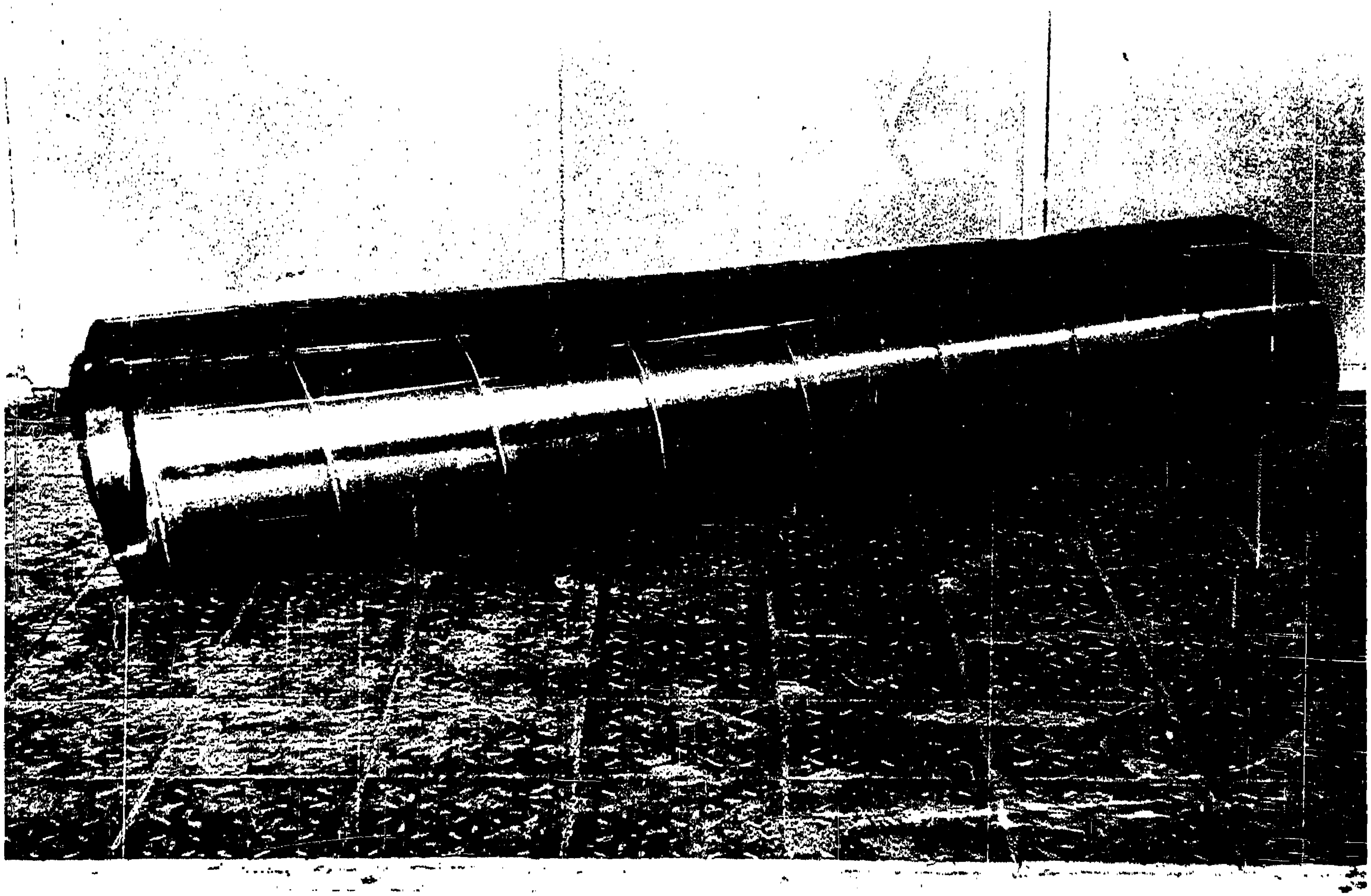
DRAWN	CHECKED	APPROVED - STRESS	APPROVED - DILS	APPROVED - WELDING	APPROVED	APPROVED -	SCALE
a/o 15 DEC. '6.							1:4

A RE: FOR EXPER. ORDER



WELDING FIXTURE FOR 20INCH DIAMETER CYLINDERS
LOW CARBON STEEL STRIP IN TRYOUT

Figure 16



20 INCH DIAMETER HELICAL BUTT WELDED CYLINDER
TRYOUT PIECE USING 11 INCH WIDE AM355 STRIP, AT 270,000 PSI Y.S.

Figure 17

Post-weld sizing of the cylindrical section will be done on a Grotnes hydraulic expander instead of employing a sizing plug, as reported in Report No. 15. The decision to make this change was based on availability of existing sizing shoes plus the greater dimensional control possible using the hydraulic expander.

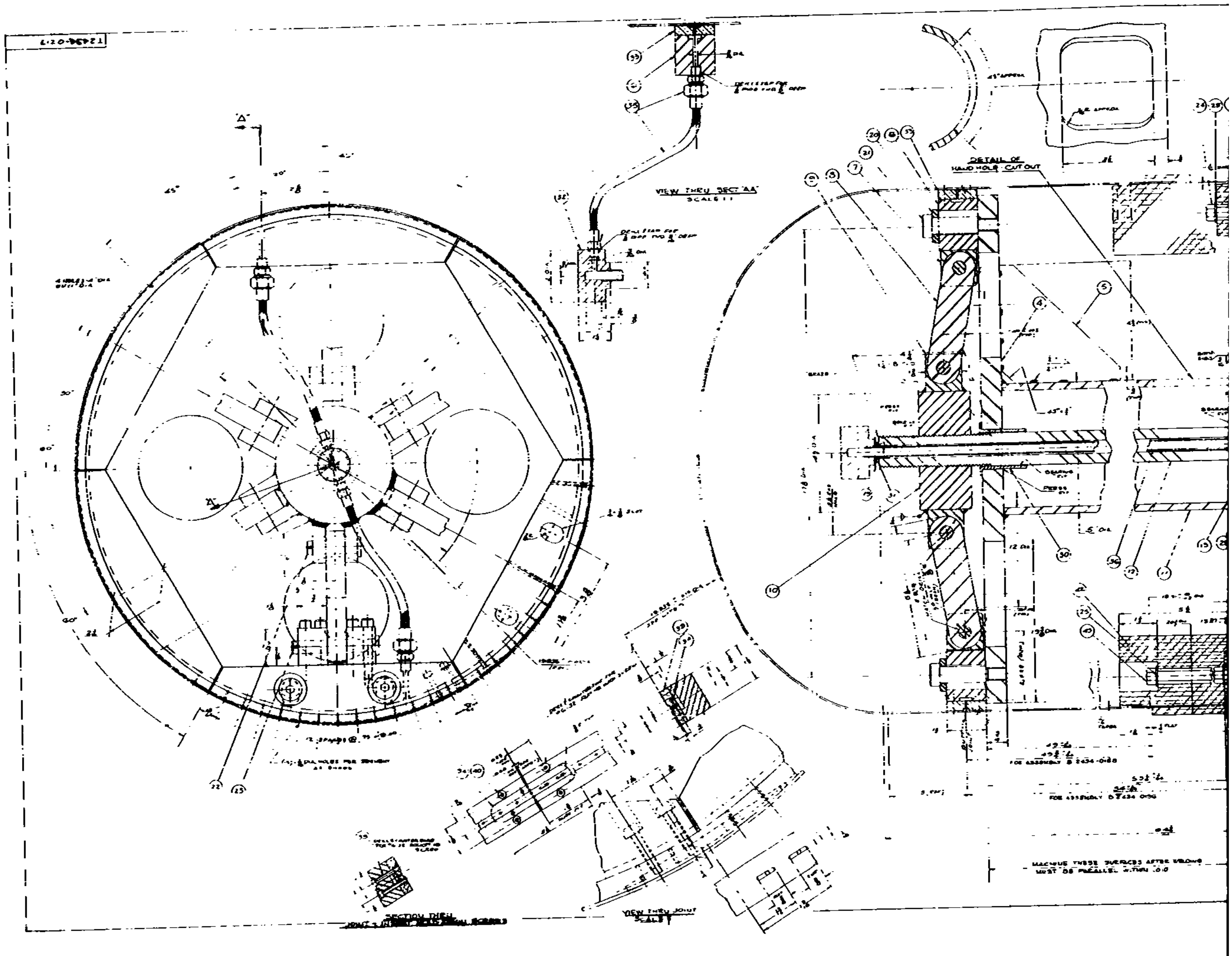
The Ti 13V-11Cr-3Al elliptical heads for the 20 inch diameter chamber were formed in a double action hydraulic press employing a proprietary sandwich method developed by The Budd Company. Figure No. 18 is a photograph of this head and cover sheets after forming and separation. A 36" diameter thin wall Type 321 S.S. hemisphere, formed in a similar manner for an atmospheric Satellite application, is shown in the center background. The manufacture of the 20% nickel steel heads is delayed pending receipt of material.

The head will be joined to the cylindrical section using the TIG welding process and employing a fixture shown in Figure No. 19, drawing T2434-0217. This fixture is designed to insure alignment of the head and shell, minimum possible mismatch at the weld joint, and adequate gas backup and chill for the welding. Inspection of weld

20 INCH DIAMETER .071 THICK ELLIPTICAL HEAD AND COVER PLATES
Ti 13V-11Cr-3Al ALLOY

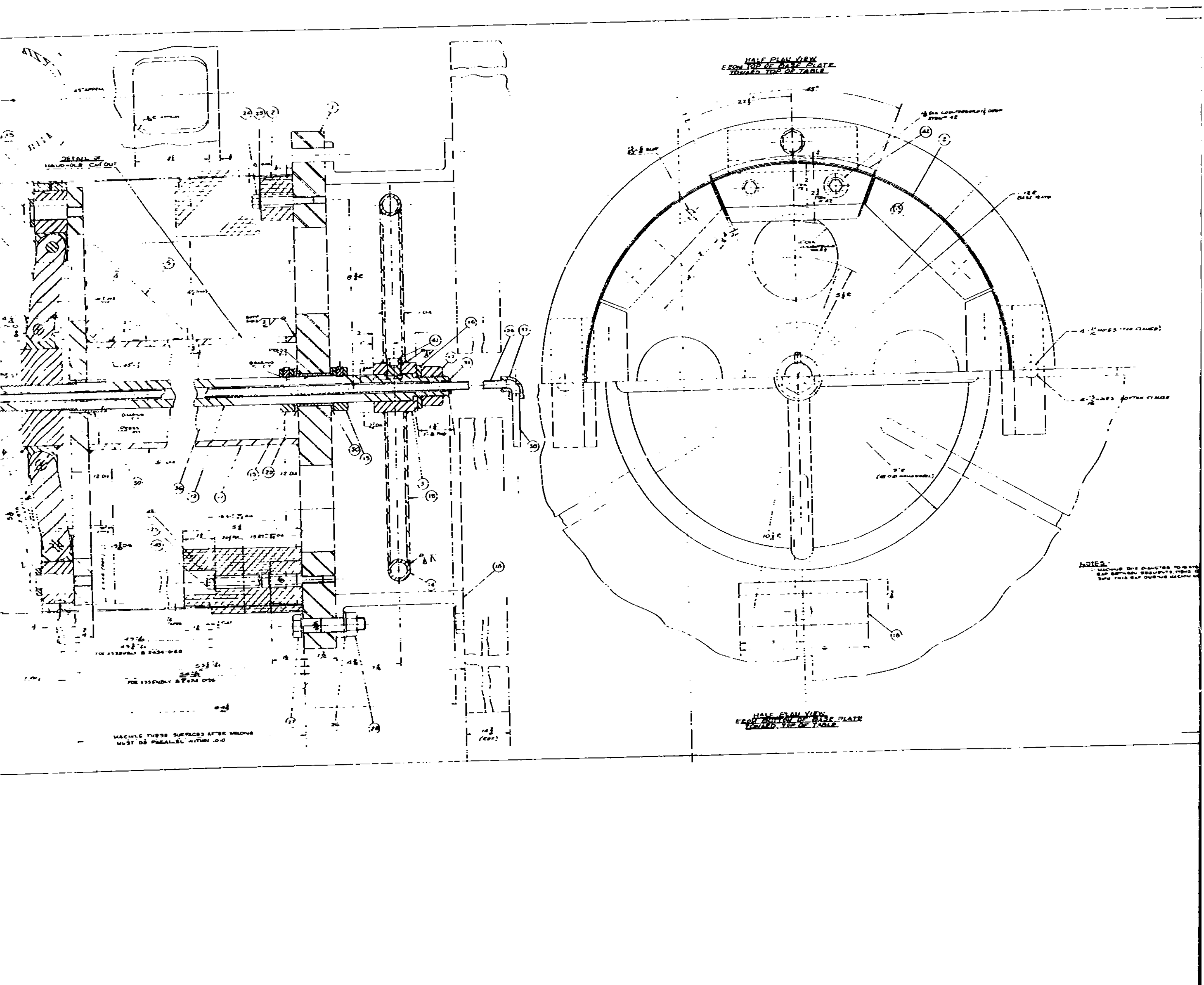
Figure 18

1



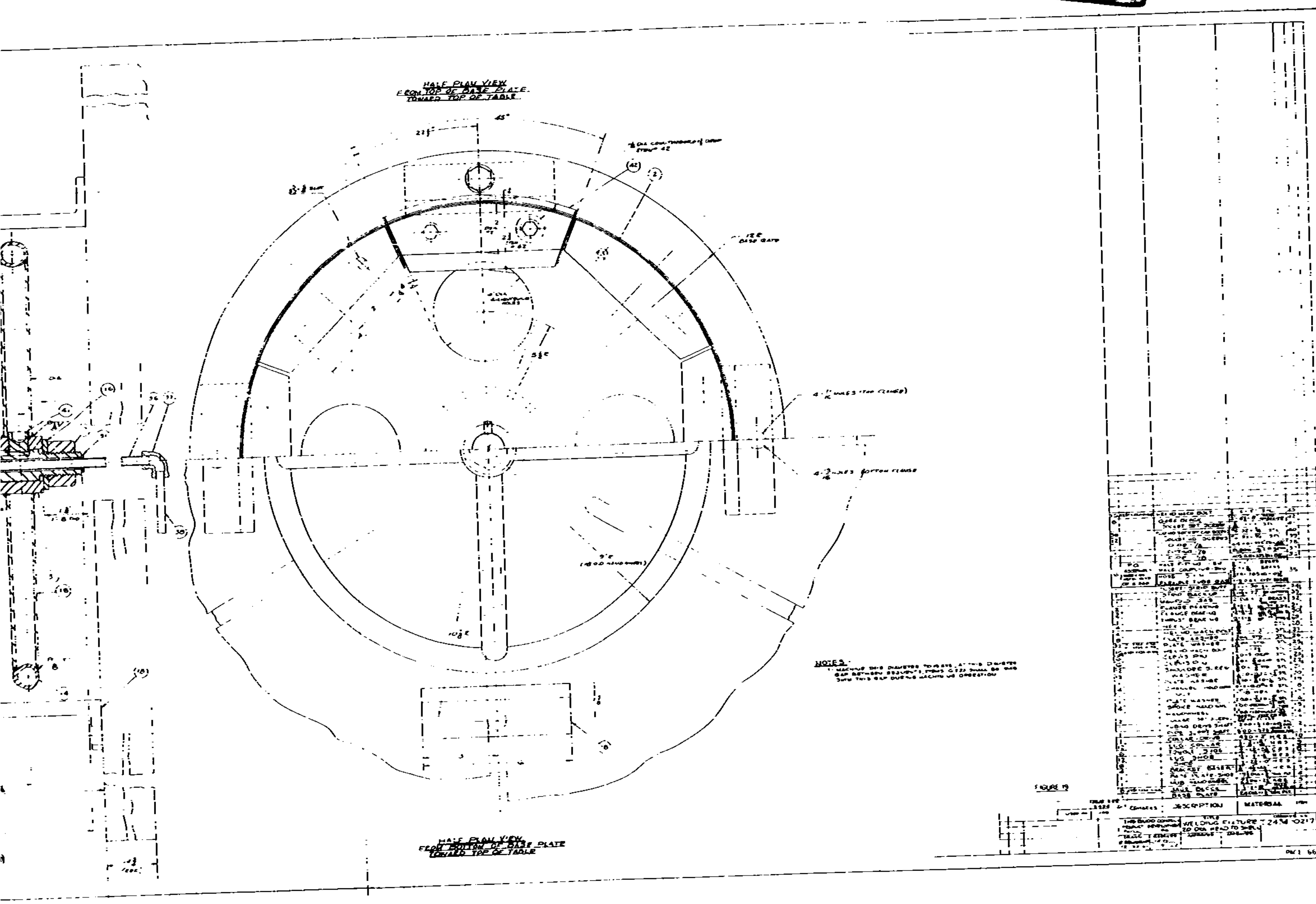
VIEW THRU SECT 'AA'
DETAIL OF HAND HOLE CUT OUT
SECTION THRU
VIEW THRU JOINT
MACHINE THESE SURFACES AFTER WELDING
MUST BE PARALLEL WITHIN .010

2



HALF PLAN VIEW
FROM TOP OF BASE PLATE
TOWARD TOP OF TABLE
DETAIL OF
HAND HOLE CUT OUT
HALF PLAN VIEW
FROM BOTTOM OF BASE PLATE
TOWARD TOP OF TABLE
MACHINE THESE SURFACES AFTER WELDING
MUST BE PARALLEL WITHIN .010
NOTES:

3



HALF PLAN VIEW
FROM TOP OF BASE PLATE
TOWARD TOP OF TABLE
NOTES
FIGURE 19
DESCRIPTION
MATERIAL
HALF PLAN VIEW
FROM BOTTOM OF BASE PLATE
TOWARD TOP OF TABLE

mismatch in the helical butt weld of the cylindrical section and in the head to shell joint will be accomplished using the gage shown in Figure No. 20, drawing D2434-0213.

ANALYSIS OF 20 INCH DIAMETER TEST CHAMBERS

For purposes of analysis, the test chamber may be divided into three principal sections - they are:

1. Cylindrical section - helical butt welded single thickness.
2. Short tapered cylinder - at end of the cylindrical section.
3. Elliptical head.

Figure Numbers 21 and 22 are charts showing the location and magnitude of the principal stresses calculated for the 20 inch diameter test chamber. Figure No. 21 shows values for the Ti 13V-11Cr-3Al alloy chamber having a wall thickness of .062, and a material yield strength of 210,000 psi. Pressure to attain a hoop stress in the cylinder equal to the yield strength is 1260 psi. Figure No. 22 shows values for the 20% nickel steel chamber, with a yield strength of 310,000 psi. Pressure to develop a hoop stress equal to the yield strength is 1240 psi. In each case the material thicknesses and strength levels are equivalent to

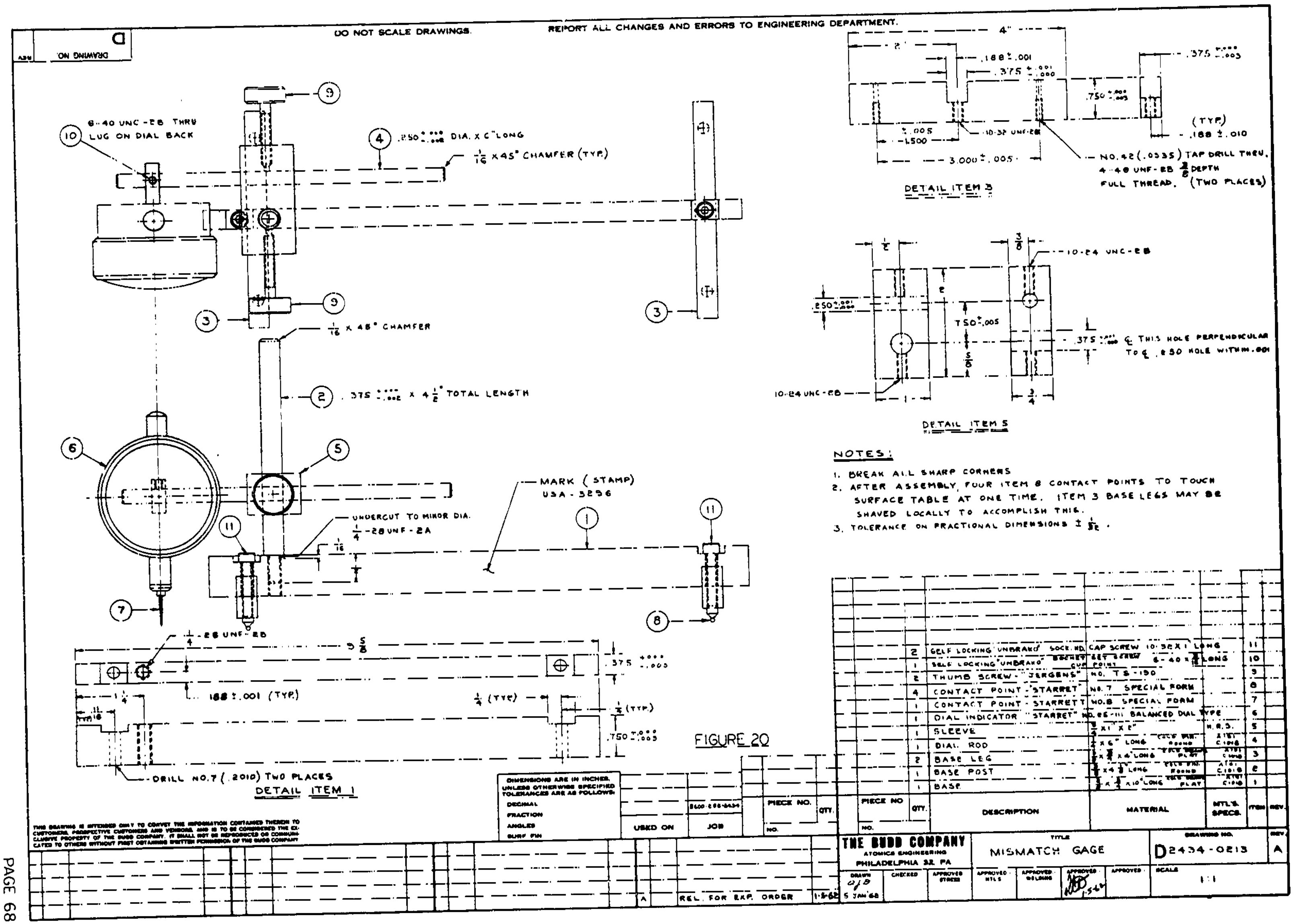
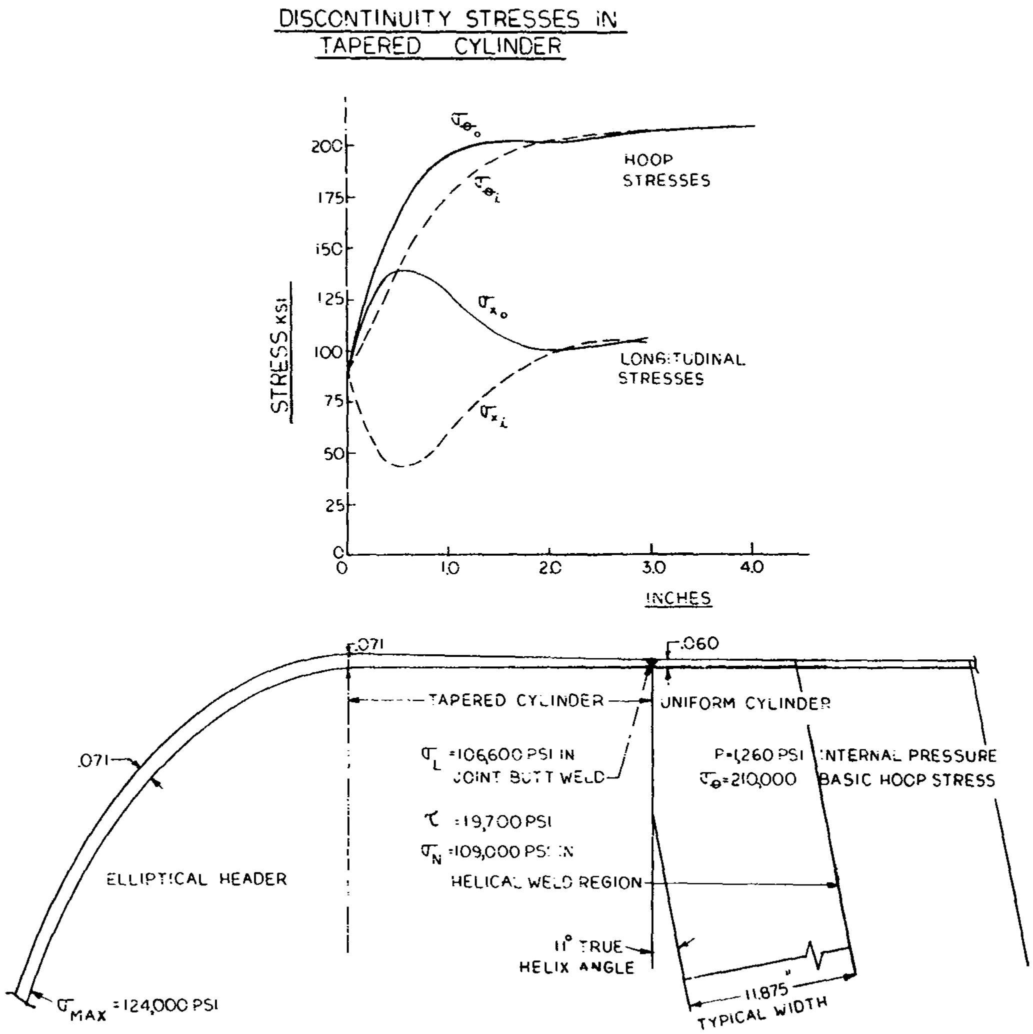

DO NOT SCALE DRAWINGS.
REPORT ALL CHANGES AND ERRORS TO ENGINEERING DEPARTMENT.
DRAWING NO.
D
6-40 UNC-2B THRU LUG ON DIAL BACK
.250 DIA. X 6" LONG
1/16 X 45° CHAMFER (TYP.)
1/16 X 45° CHAMFER
.375 X 4 1/2" TOTAL LENGTH
MARK (STAMP) USA-3256
UNDERCUT TO MINOR DIA.
1/4-28 UNF-2A
1/4-28 UNF-2B
5 5/8
.188 ±.001 (TYP.)
1/4 (TYP.)
.750
DRILL NO. 7 (.2010) TWO PLACES
DETAIL ITEM 1
4"
2"
.188 ±.001
.375
.750
.375
10-32 UNF-2B
1.500
±.005
3.000 ±.005
(TYP.)
.188 ±.010
NO. 42 (.0935) TAP DRILL THRU, 4-40 UNF-2B 3/8 DEPTH FULL THREAD, (TWO PLACES)
DETAIL ITEM 3
10-24 UNC-2B
.250
.750 ±.005
5/8
.375 ℄ THIS HOLE PERPENDICULAR TO ℄ .250 HOLE WITHIN .001
10-24 UNC-2B
3/4
DETAIL ITEM 5
NOTES:
1. BREAK ALL SHARP CORNERS
2. AFTER ASSEMBLY, FOUR ITEM 8 CONTACT POINTS TO TOUCH SURFACE TABLE AT ONE TIME. ITEM 3 BASE LEGS MAY BE SHAVED LOCALLY TO ACCOMPLISH THIS.
3. TOLERANCE ON FRACTIONAL DIMENSIONS ± 1/32.
2 | SELF LOCKING "UNBRAKO" SOCK. HD. CAP SCREW 10-32 X 1 LONG | 11
1 | SELF LOCKING "UNBRAKO" SOCKET SET SCREW CUP POINT 6-40 X 1/4 LONG | 10
2 | THUMB SCREW - "JERGENS" NO. TS-150 | 9
4 | CONTACT POINT - "STARRETT" NO. 7 SPECIAL FORM | 8
1 | CONTACT POINT - "STARRETT" NO. 8 SPECIAL FORM | 7
1 | DIAL INDICATOR "STARRETT" NO. 25-111 BALANCED DIAL TYPE | 6
1 | SLEEVE | X 1 X 2" | H.R.S. | 5
1 | DIAL ROD | X 6" LONG | COLD FIN. ROUND | C1018 | 4
2 | BASE LEG | X 4 LONG | COLD FIN. FLAT | C1018 | 3
1 | BASE POST | X 4 LONG | COLD FIN. ROUND | C1018 | 2
1 | BASE | X 10" LONG | COLD FIN. FLAT | C1018 | 1
QTY. | PIECE NO. | NO. | DESCRIPTION | MATERIAL | MTL'S. SPECS. | ITEM | REV.
DIMENSIONS ARE IN INCHES. UNLESS OTHERWISE SPECIFIED TOLERANCES ARE AS FOLLOWS:
DECIMAL
FRACTION
ANGLES
SURF. FIN.
USED ON | JOB | PIECE NO. | QTY.
A | REL. FOR EXP. ORDER | 1-5-62
THE BUDD COMPANY
ATOMICS ENGINEERING
PHILADELPHIA 32, PA
DRAWN
5 JAN '62
CHECKED
APPROVED STRESS
APPROVED MTLS
APPROVED WELDING
APPROVED
TITLE
MISMATCH GAGE
DRAWING NO.
D2434-0213
REV.
A
SCALE
1:1
THIS DRAWING IS INTENDED ONLY TO CONVEY THE INFORMATION CONTAINED THEREIN TO CUSTOMERS, PROSPECTIVE CUSTOMERS AND VENDORS, AND IS TO BE CONSIDERED THE EXCLUSIVE PROPERTY OF THE BUDD COMPANY. IT SHALL NOT BE REPRODUCED OR COMMUNICATED TO OTHERS WITHOUT FIRST OBTAINING WRITTEN PERMISSION OF THE BUDD COMPANY

FIGURE 20

20" DIAMETER TEST CHAMBER
Ti 13V-11CR-3AL-ALLOY

SUMMARY OF PRINCIPAL CALCULATED STRESSES AND MAT'L PROPERTIES



	ANNEALED	SOLUTION ANNLD AND AGED	COLD ROLLED AND AGED	AS WELDED
Y.S.	135,000	190,000	210,000	135,000
T.S.	140,000	215,000	215,000	140,000
EL.	20 %	4 %	2-3 %	—

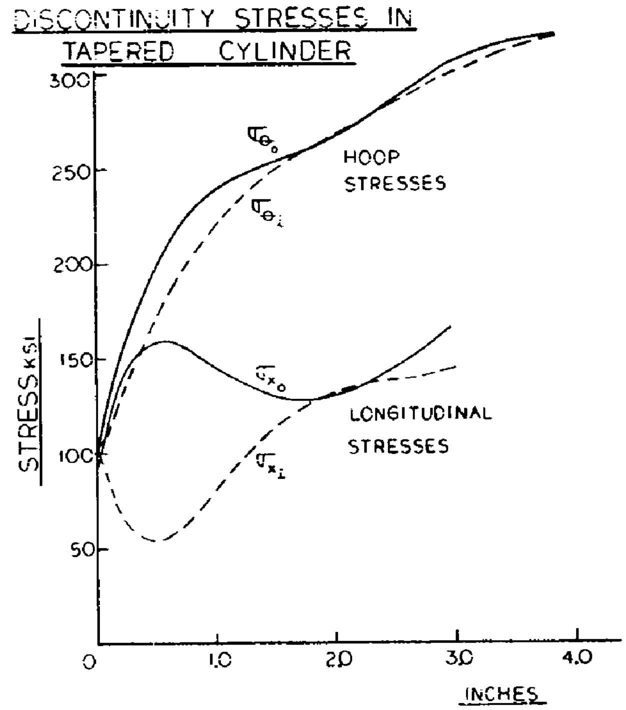
FIGURE 21

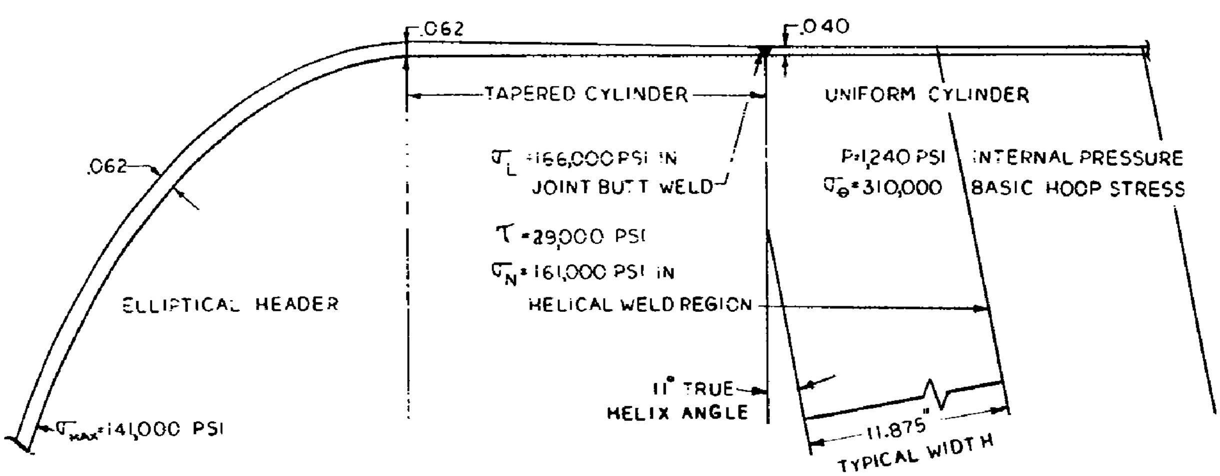
DWG NO 2434-0222

20" DIAMETER TEST CHAMBER

20% NICKEL STEEL

SUMMARY OF PRINCIPAL CALCULATED STRESSES AND MAT'L PROPERTIES





	ANNEALED	ANNEALED SUB-ZERO COOLED AGED	COLD ROLLED	COLD ROLLED SUB-ZERO COOLED AGED	AS WELDED	WELD SUB-ZERO COOL'D AGED
Y.S.	130,000	290,000	170,000	310,000	125,000	225,000
T.S.	170,000	310,000	240,000	315,000	170,000	245,000
EL.	8 %	3 %	6 %	3 %	--	--
R_c	34	58	42	58	--	--

FIGURE 22

DWG. NO. 2434-0223

the prototype 40 inch diameter chamber.

The cylindrical section is subjected primarily to membrane stress, except near the ends of the cylinder where secondary stresses due to discontinuities are present. A gradual taper is introduced at the cylinder ends to relieve these discontinuity effects. The stresses in the tapered section are discussed later in this section.

Symbols used in this discussion are shown in Figure Numbers 23 and 24.

For a specific material in the "as-welded" condition the yield theory which most closely approximates actual behavior was chosen as follows: A group of specimens were tested uniaxially at different ratios of normal to shear stresses (different weld line angles). A plot of the data results in a curve shown in Figure No. 25. The coefficient (a) in the following expressions is determined from this curve.

SYMBOLS :

a	RADIUS OR MAJOR SEMI-AXIS OF ELLIPSOID
b	MINOR SEMI-AXIS OF ELLIPSOID
B	COLUMN MATRIX OF MEMBRANE DEFLECTIONS
C	CONSTANTS OF INTEGRATION
D	$Et^3/12(1-\nu^2)$
E	MODULUS OF ELASTICITY
ℓ	LENGTH OF TAPERED SHELL
M	BENDING MOMENT
p	PRESSURE
Q	EDGE SHEAR
t	THICKNESS
w	DEFLECTION (POSITIVE OUTWARDS)
x	AXIAL DISTANCE
y	$2\rho\sqrt{x/a}$
Z	COEFFICIENT MATRIX
α	RATE OF CHANGE OF THICKNESS (dt/dx)
β	$\sqrt[4]{3(1-\nu^2)}/\sqrt{at}$
ν	POISSON'S RATIO (.30)
ρ	$\sqrt[4]{12(1-\nu^2)}/\sqrt{\alpha}$
σ, τ	STRESS
σ_o	WELD MATERIAL YIELD STRENGTH

SUBSCRIPTS :

H	HEADER
L	LARGE END OF TAPERED SHELL
m	MEMBRANE
S	SMALL END OF TAPERED SHELL
T	TAPERED CYLINDER
U	UNIFORM CYLINDER
X	AXIAL OR LONGITUDINAL
ϕ	MERIDIONAL
θ	HOOP OR CIRCUMFERENTIAL
i	INSIDE SURFACE
o	OUTSIDE SURFACE
N	NORMAL

FIG. 23

SYMBOLS USED IN COMPUTER PROGRAM:

ALPHA	α
A	a
BERD	ber'
BETA	β
CER	ker
CERD	ker'
DELTX	Δx
FNT	$(N_\theta)_{TOTAL}$
P	p
RHO	ρ
STI	$(\sigma_{TOTAL})_{INSIDE}$
STO	(σ_{TOTAL}) OUTSIDE
SXB	(σ_x) BENDING
T	t
TL	t_L
TS	t_s
XLEN	ℓ
XL	x_L
XS	x_s
Y	y
Z(I,J)	z_{ij}

FIGURE 24

EFFECT OF HELIX ANGLE ON THE YIELD STRENGTH OF A CYLINDER

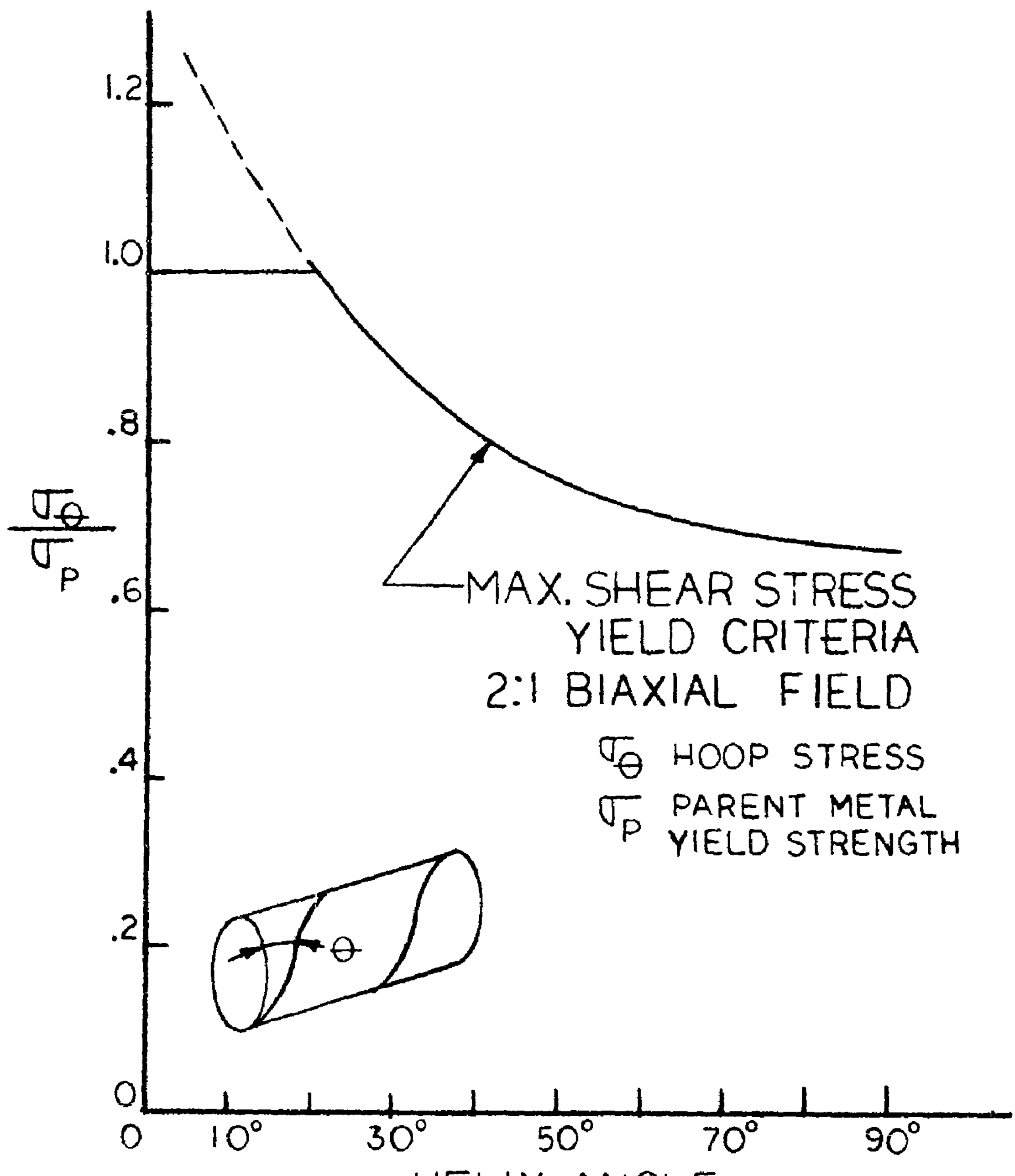


FIG. 25

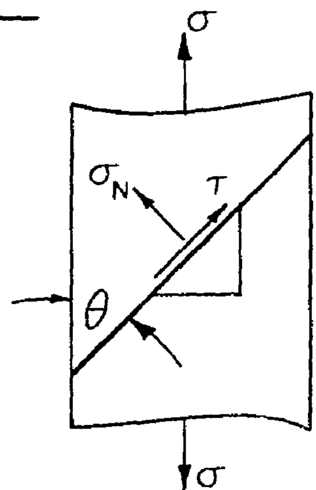
The mathematical theory used is as follows:

A. <u>Stress orientation in uniaxial tensile test</u>

At equilibrium:

$$\sigma_N = \sigma \sin^2\theta$$

$$\tau = \frac{\sigma}{2} \sin 2\theta$$



B. <u>Use of stress theories</u>

The maximum shear stress theory is given by:

$$(1) \qquad \left(\frac{\sigma}{\sigma_o}\right)^2 + 4\left(\frac{\tau}{\sigma_o}\right)^2 = 1$$

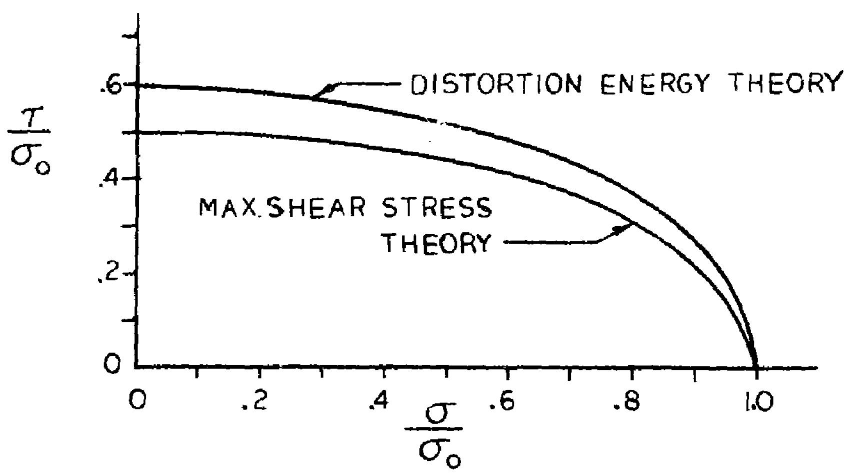
and the distortion energy theory is represented by:

$$(2) \qquad \left(\frac{\sigma}{\sigma_o}\right)^2 + 3\left(\frac{\tau}{\sigma_o}\right)^2 = 1$$

or by substituting a coefficient (a), both equations can be written as

$$(3) \qquad \left(\frac{\sigma}{\sigma_o}\right)^2 + a\left(\frac{\tau}{\sigma_o}\right)^2 = 1$$

A plot of equations (1) and (2) yields the following type curves:



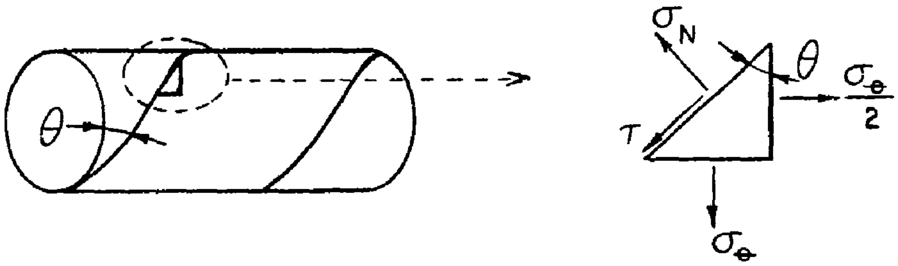
C. <u>Applied to Cylinder Design</u>:

let:

σ_θ = hoop stress

σ_p = yield strength of parent metal

then:



where at equilibrium:

$$\sigma_N = \frac{\sigma_\theta}{2}\left(1 + \sin^2\theta\right)$$

$$\tau = \frac{\sigma_\theta}{4}\left(\sin 2\theta\right)$$

and the assumed yield criteria is:

$$\left(\frac{\sigma_N}{\sigma_o}\right)^2 + a\left(\frac{\tau}{\sigma_o}\right)^2 = 1 \qquad (4)$$

where (a) is adjusted to fit the data.

In terms of the hoop stress and helix angle, equation (4) may be rewritten as follows:

$$\frac{\sigma_\theta}{\sigma_p} = \frac{2\left(\frac{\sigma_o}{\sigma_p}\right)}{\sqrt{\left(1+\sin^2\theta\right)^2 + \frac{a}{4}\sin^2 2\theta}}$$

If $\frac{\sigma_\theta}{\sigma_p}$ exceeds (1), the parent metal will yield. Where $\frac{\sigma_o}{\sigma_p}$ and (a) are material properties, and θ is geometry dependent, they are quantatively related as shown in Figure 25.

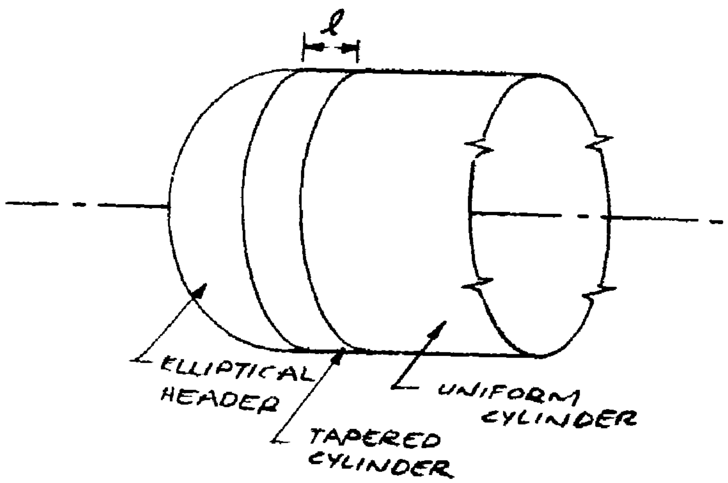
The short, tapered cylinder is the transition zone between the uniform cylinder and the elliptical head. Since the cylinder and head are of different thickness and therefore experience different membrane deflections, the discontinuity is quite severe. However, the addition of the tapered section results in total stresses which are within the required limits. Application of the theory upon which the discontinuity stresses are found is discussed in the following pages.

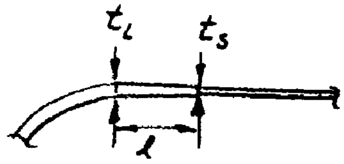
DISCONTINUITY STRESSES IN SHORT, TAPERED CYLINDERS

FOR A SHORT, TAPERED CYLINDER USED AS THE TRANSITION JOINT BETWEEN A CYLINDRICAL PRESSURE VESSEL AND AN ELLIPTICAL HEAD. THE MEMBRANE STRESSES ARE:

$$\sigma_\theta = pa/t$$

$$\sigma_x = pa/2t$$



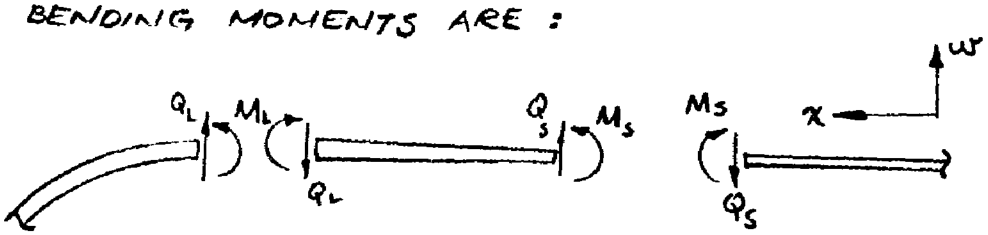


CROSS SECTION OF JOINT

TO THESE MEMBRANE STRESSES MUST BE ADDED THE DISCONTINUITY STRESSES DUE TO BENDING AND SHEAR IN THE JOINT.

COMPATABILITY CONDITIONS REQUIRE THE DEFLECTION AND SLOPE AT EITHER END OF THE TAPERED CYLINDER BE EQUAL TO THOSE OF THE HEADER AND UNIFORM CYLINDER, RESPECTIVELY.

THE DISCONTINUITY EDGE SHEARS AND BENDING MOMENTS ARE:



MEMBRANE SOLUTION IN UNIFORM CYLINDER *:

$$\omega_m = \frac{(1-\nu/2)}{E} \frac{pa^2}{t} \qquad \omega'_m = 0$$

MEMBRANE SOLUTION IN ELLIPTICAL HEAD:

$$\omega_m = \frac{pa^2}{2Et}\left[2-\nu-\left(\frac{a}{b}\right)^2\right] \qquad \omega'_m = 0$$

MEMBRANE SOLUTION IN TAPERED CYLINDER **:

$$\omega_m = \frac{(1-\nu/2)}{E} \frac{pa^2}{x\alpha}$$

$$\omega'_m = -\frac{(1-\nu/2)}{E} \frac{pa^2}{x^2\alpha}$$

DISCONTINUITY SOLUTION IN UNIFORM CYLINDER AND ELLIPTICAL HEADER *:

$$\omega = \frac{1}{2\beta^3 D}\left[\beta M + Q\right]$$

$$\omega' = \frac{-1}{2\beta^2 D}\left[2\beta M + Q\right]$$

DISCONTINUITY SOLUTION IN TAPERED CYLINDER **:

$$\omega = \frac{1}{\sqrt{x}}\left[C_1 \, ber' y + C_2 \, bei' y + C_3 \, ker' y + C_4 \, kei' y\right]$$

$$\omega' = \frac{-1}{2x\sqrt{x}}\Big[C_1(2\, ber' y + y \, bei \, y) + C_2(2\, bei' y - y\, ber \, y) + C_3(2\, ker' y + y\, kei\, y) + C_4(2\, kei' y - y\, ker\, y)\Big]$$

* TIMOSHENKO, S.: THEORY OF PLATES & SHELLS, McGRAW-HILL BOOK CO., 1940

** FLÜGGE, W.: STRESSES IN SHELLS, SPRINGER-VERLAG, 1960

$$M_x = \frac{E\alpha^3\sqrt{x}}{48(1-\nu^2)}\Big[c_1(-y^2 \,bei'y + 4y\, bei\, y + 8\, ber'y) + c_2(y^2\, ber'y - 4y\, ber\, y + 8\, bei'y) + c_3(-y^2\, kei'y + 4y\, kei\, y + 8\, ker'y) + c_4(y^2\, ker'y - 4y\, ker\, y + 8\, kei'y)\Big]$$

$$Q_x = \frac{E\alpha^2\sqrt{x}}{4\sqrt{3(1-\nu^2)}\,a}\Big[c_1(-y\, ber\, y + 2\, bei'y) - c_2(y\, bei\, y + 2\, ber'y) + c_3(-y\, ker\, y + 2\, kei'y) - c_4(y\, kei\, y + 2\, ker'y)\Big]$$

COMBINING THE ABOVE EQS. & THE COMPATABILITY CONDITION :

AT SMALL END :

$$(\omega_m)_u + \alpha_{1S} M_S - \alpha_{2S} Q_S = (\omega_m)_T + \alpha_1 c_1 + \alpha_2 c_2 + \alpha_3 c_3 + \alpha_4 c_4$$

$$\alpha_{1S}' M_S - \alpha_{2S}' Q_S = (\omega_m')_T + \alpha_5 c_1 + \alpha_6 c_2 + \alpha_7 c_3 + \alpha_8 c_4$$

$$M_S = \alpha_9 c_1 + \alpha_{10} c_2 + \alpha_{11} c_3 + \alpha_{12} c_4$$

$$Q_S = \alpha_{13} c_1 + \alpha_{14} c_2 + \alpha_{15} c_3 + \alpha_{16} c_4$$

AT LARGE END :

$$(\omega_m)_H + \alpha_{1L} M_L + \alpha_{2L} Q_L = (\omega_n)_T + \alpha_{17} c_1 + \alpha_{18} c_2 + \alpha_{19} c_3 + \alpha_{20} c_4$$

$$\alpha_{1L}' M_L + \alpha_{2L}' Q_L = (\omega_m')_T + \alpha_{21} c_1 + \alpha_{22} c_2 + \alpha_{23} c_3 + \alpha_{24} c_4$$

$$M_L = \alpha_{25} c_1 + \alpha_{26} c_2 + \alpha_{27} c_3 + \alpha_{28} c_4$$

$$Q_L = \alpha_{29} c_1 + \alpha_{30} c_2 + \alpha_{31} c_3 + \alpha_{32} c_4$$

WHERE $\alpha_{ij} = f(ber, ker, etc)$

THESE EIGHT EQS. MAY BE WRITTEN AS:

$$\Big[\; Z \;\Big]\begin{Bmatrix} c_1 \\ c_2 \\ M_S \\ Q_S \\ c_3 \\ c_4 \\ M_L \\ Q_L \end{Bmatrix} = \Big\{\; B \;\Big\}$$

WHERE :

$B_i = f(\omega_m, \omega_m')$

$Z_{ij} = f(\alpha_{ij})$

THE STRESSES IN THE TAPERED CYLINDER MAY BE DETERMINED AFTER THE EDGE SHEARS AND MOMENTS, AND CONSTANTS C_1 TO C_4 ARE SOLVED FOR.

$$\begin{Bmatrix} C_1 \\ C_2 \\ M_S \\ Q_S \\ C_3 \\ C_4 \\ M_L \\ Q_L \end{Bmatrix} = \begin{bmatrix} Z^{-1} \end{bmatrix} \begin{Bmatrix} B \end{Bmatrix}$$

THE TOTAL STRESSES ARE THEN:

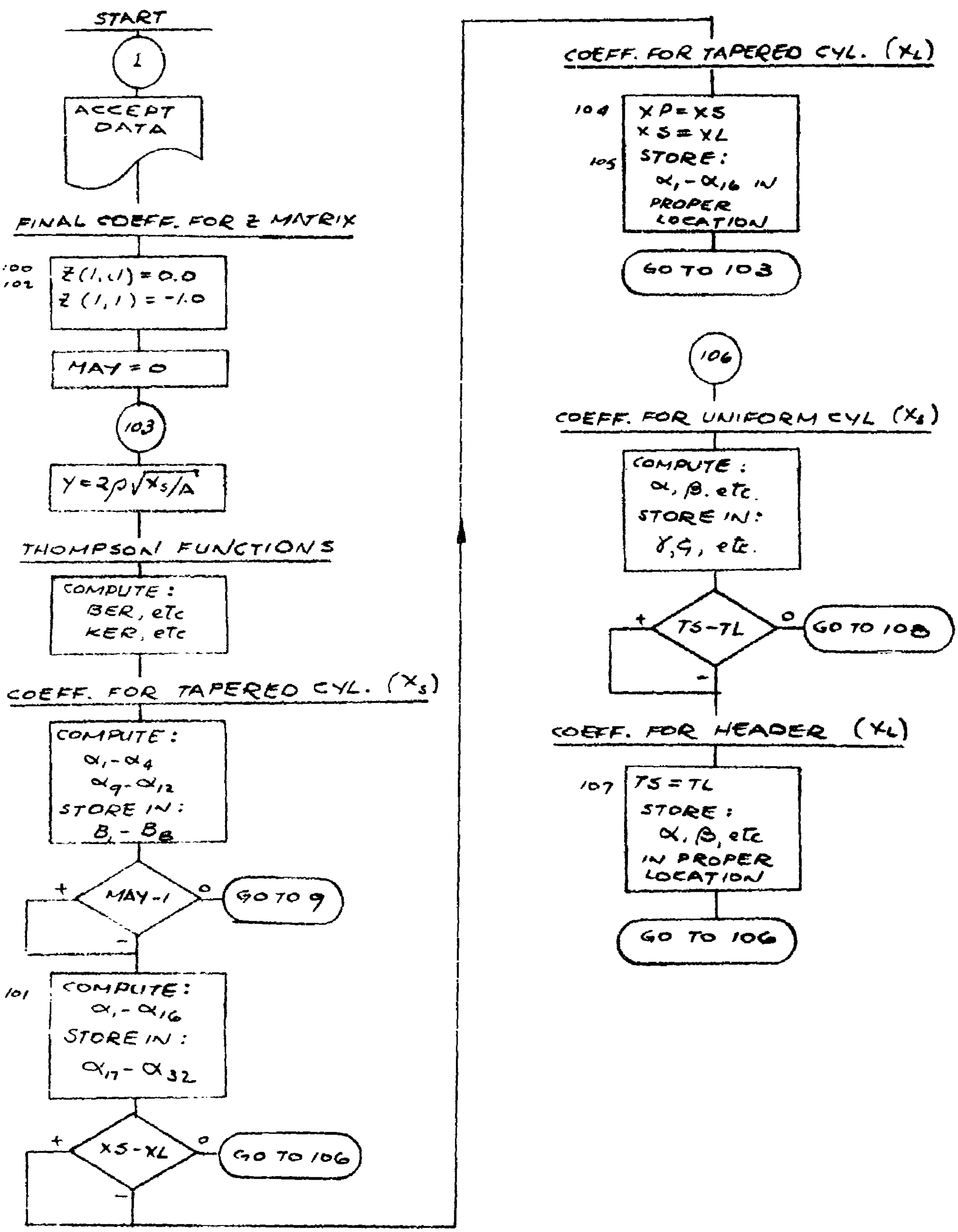
$$\sigma_\theta = \frac{pa}{t} + \frac{Ew}{a} \pm \nu \frac{6M}{t^2}$$

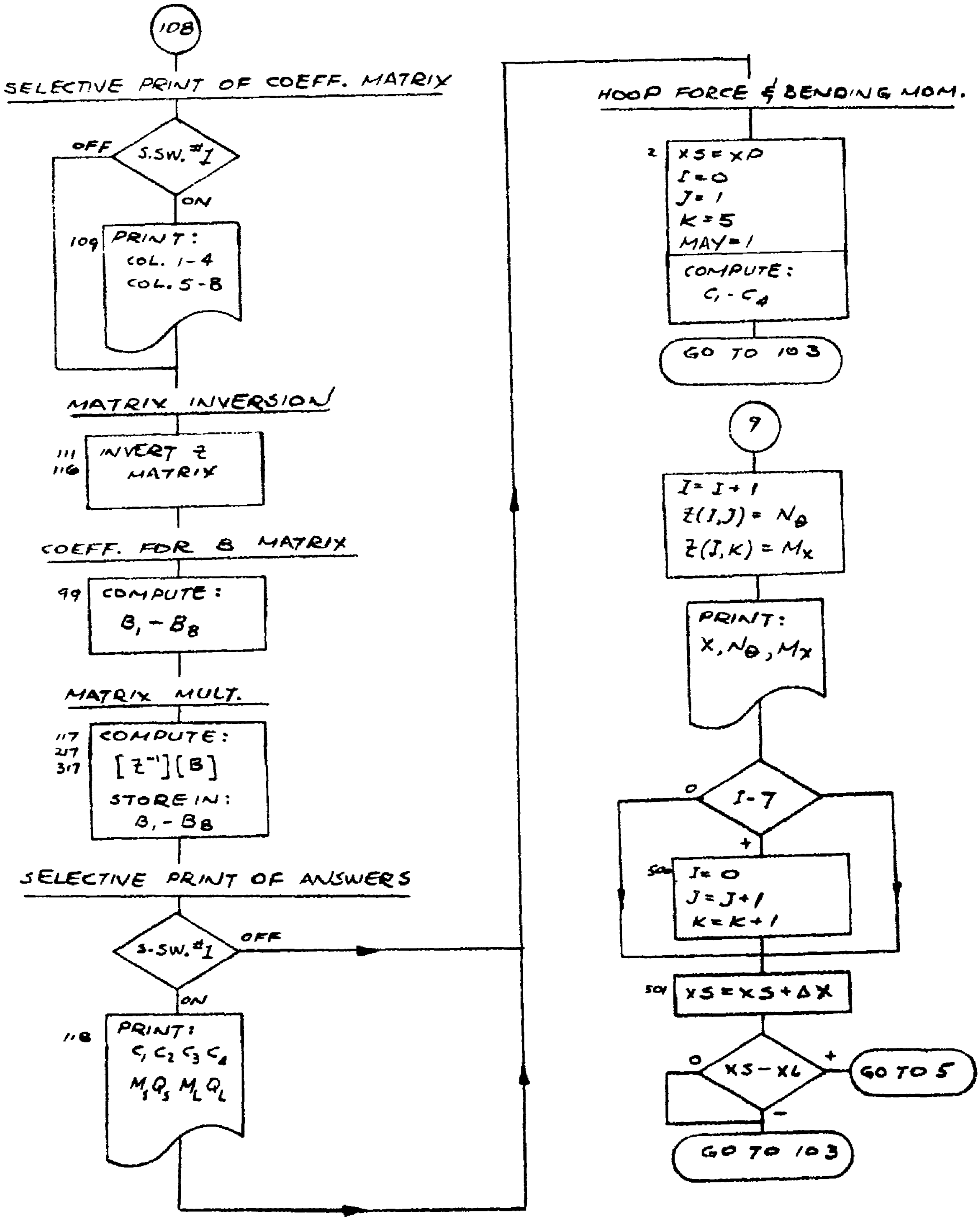
$$\sigma_x = \frac{pa}{2t} \pm \frac{6M}{t^2}$$

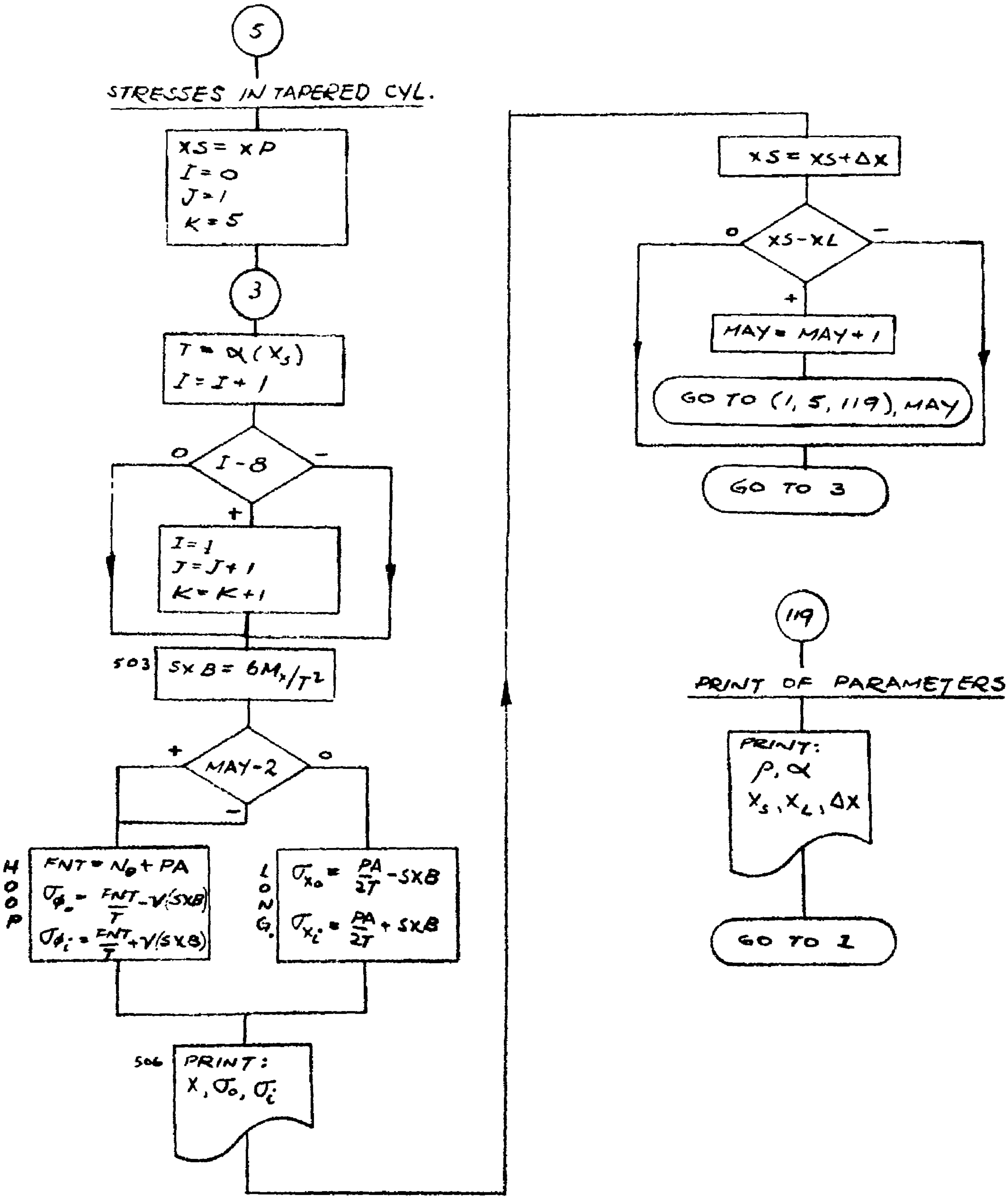
ON THE FOLLOWING PAGES IS THE COMPUTER PROGRAM, WRITTEN IN FORTRAN LANGUAGE, TO FIND THE STRESSES. THE ONLY INPUT INFORMATION IS THE DATA: t_s, t_L, ℓ, a, E, p.

FLOW CHART:

PROGRAM TO COMPUTE STRESSES IN SHORT, TAPERED CYLINDER




108
SELECTIVE PRINT OF COEFF. MATRIX
S.SW. #1
OFF
ON
109 PRINT: COL. 1-4 COL. 5-8
MATRIX INVERSION
111 116 INVERT Z MATRIX
COEFF. FOR B MATRIX
99 COMPUTE: B1 - B8
MATRIX MULT.
117 217 317 COMPUTE: [Z-1][B] STORE IN: B1 - B8
SELECTIVE PRINT OF ANSWERS
S.SW. #1
OFF
ON
118 PRINT: C1 C2 C3 C4 MS QS ML QL
HOOP FORCE & BENDING MOM.
2 XS = XP I = 0 J = 1 K = 5 MAY = 1
COMPUTE: C1 - C4
GO TO 103
9
I = I + 1 Z(I,J) = Nθ Z(I,K) = Mx
PRINT: X, Nθ, Mx
I-7
0
+
500 I = 0 J = J+1 K = K+1
501 XS = XS + ΔX
XS - XL
0
+
-
GO TO 5
GO TO 103


5
STRESSES IN TAPERED CYL.
XS = XP
I = 0
J = 1
K = 5
3
T = α(Xs)
I = I + 1
I - 8
I = 1
J = J + 1
K = K + 1
503
SXB = 6Mx/T²
MAY-2
HOOP
FNT = Nφ + PA
σφo = FNT/T - ν(SXB)
σφi = FNT/T + ν(SXB)
LONG.
σxo = PA/2T - SXB
σxi = PA/2T + SXB
506
PRINT:
X, σo, σi
XS = XS + ΔX
XS - XL
MAY = MAY + 1
GO TO (1, 5, 119), MAY
GO TO 3
119
PRINT OF PARAMETERS
PRINT:
ρ, α
Xs, XL, ΔX
GO TO 1

```
16000100000RS
LOAD SOURCE DECK
THEN PUSH START
36004210010ORS
07176
4900402

C     PROGRAM TO COMPUTE STRESSES IN SHORT TAPERED CYLINDER
      DIMENSION   Z(8,8),B(8)
    1 ACCEPT, TS,TL,XLEN,A,E,P
      XS=(XLEN)/((TL/TS)-1.0)
      XL=XS+XLEN
      ALPHA=TS/XS
      DELTX=XLEN/30.0
      RHO=SQR(SQR((10.92)/(ALPHA**2)))
C         FINAL COEFF. FOR MATRIX Z
      DO 100 I=1,8
      DO 100 J=1,8
  100 Z(I,J)=0.0
      DO 102 I=3,8
  102 Z(I,I)=-1.0
      MAY=0
  103 Y=(2.0*RHO)*(SQR(XS/A))
C         THOMSON FUNCTIONS
      X=(EXP(Y/1.414214))/(SQR(6.2831853*Y))
      BER=(X)*(COS((Y/1.414214)-.3926991))
      BEI=(X )*(SIN((Y/1.414214)-.3926991))
      BERD=(X )*(COS((Y/1.414214)+.3926991))
      BEID=(X )*(SIN((Y/1.414214)+.3926991))
      X=(EXP(-Y/1.414214))*(SQR(1.5707963/Y))
      CER=(X)*(COS((Y/1.414214)+.3926991))
      CEI=-(X )*(SIN((Y/1.414214)+.3926991))
      CERD=-(X)*(COS((Y/1.414214)-.3926991))
      CEID=(X )*(SIN((Y/1.414214)-.3926991))
C         COEFF. FOR TAPERED CYL., ORIGIN AT SMALL END (XS)
      X=1.0/SQR(XS)
      B(1)=X*BERD
      B(2)=X*BEID
      B(3)=X*CERD
      B(4)=X*CEID
      X=E*(((ALPHA)**3)*(SQR(XS)))/(43.68)
      YS=Y**2
      B(5)  =X*(-(YS)*BEID+4.0*Y*BEI+8.0*BERD)
      B(6)  =X*((YS)*BERD-4.0*Y*BER+8.0*BEID)
      B(7)  =X*(-(YS)*CEID+4.0*Y*CEI+8.0*CERD)
      B(8)  =X*((YS)*CERD-4.0*Y*CER+8.0*CEID)
      IF (MAY-1) 101,9,101
  101 Z(5,1)=B(1)
      Z(5,2)=B(2)
      Z(5,5)=B(3)
      Z(5,6)=B(4)
      Z(7,1)=B(5)
      Z(7,2)=B(6)
      Z(7,5)=B(7)
      Z(7,6)=B(8)
      X1=(-1.0)/(2.0*XS*SQR(XS))
      Z(6,1)=X1*(2.0*BERD+Y*BEI)
      Z(6,2)=X1*(2.0*BEID-Y*BER)
      Z(6,5)=X1*(2.0*CERD+Y*CEI)
```

```
      Z(6,6)=X1*(2.0*CEID-Y*CER)
      X=(E/X1)*(((ALPHA)**2)*(SQR(XS)))/(A*6.6090846)
      Z(8,1)=(Z(6,2)*X)
      Z(8,2)=-(Z(6,1)*X)
      Z(8,5)=(Z(6,6)*X)
      Z(8,6)=-(Z(6,5)*X)
      IF (XS-XL) 104,106,104
C            COEFF. FOR TAPERED CYL., ORIGIN AT LARGE END (XL)
  104 XP=XS
      XS=XL
      DO 105 I=1,4
      J=I+4
      Z(I,1)=Z(J,1)
      Z(I,2)=Z(J,2)
      Z(I,5)=Z(J,5)
  105 Z(I,6)=Z(J,6)
      GO TO 103
C            COEFF. FOR UNIFORM CYL., ORIGIN AT SMALL END (XS)
  106 D=(E*(TS)**3)/(10.92)
      BETA=SQR(SQR((2.73)/((A**2)*(TS**2))))
      Z(5,7)=(-1.0)/(2.0*(BETA**2)*D)
      Z(5,8)= Z(5,7)/(BETA)
      Z(6,7)=-Z(5,7)*(2.0*BETA)
      Z(6,8)=-Z(5,7)
      IF (TS-TL) 107,108,107
C            COEFF. FOR HEADER, ORIGIN AT LARGE END (XL)
  107 TS=TL
      Z(1,3)=Z(5,7)
      Z(1,4)=-Z(5,8)
      Z(2,3)=-Z(6,7)
      Z(2,4)=Z(6,8)
      GO TO 106
C     SELECTIVE PRINT OF COEFFICIENT MATRIX
  108 IF (SENSE SWITCH 1) 109,111
  109 DO 110 I=1,8
  110 PRINT, Z(I,1),Z(I,2),Z(I,3),Z(I,4)
      DO 210 I=1,8
  210 PRINT, Z(I,5),Z(I,6),Z(I,7),Z(I,8)
C            MATRIX INVERSION (Z)-1
  111 DO 115 K=1,8
      C=Z(K,K)
      Z(K,K)=1.0
      DO 113 J=1,8
  113 Z(K,J)=Z(K,J)/C
      DO 115 I=1,8
      IF(I-K) 114,115,114
  114 C=Z(I,K)
      Z(I,K)=0.0
      DO 116 J=1,8
  116 Z(I,J)=Z(I,J)-C*Z(K,J)
  115 CONTINUE
C            COEFF. FOR B MATRIX
      TS=ALPHA*XP
      DO 99 I=1,8
   99 B(I)=0.0
      B(2)=(0.85*(A**2)*P)/(TS*XP*E)
      B(5)=((P*(A**2))/(E*TL))*(-0.98)
      B(6)=(B(2))*((TS*XP)/(TL* XL))
C            MATRIX MULT.
      DO 117 I=1,8
```

```
      C=0.0
      DO 217 K=1,8
  217 C=Z(I,K)*B(K)+C
  117 Z(1,I)=C
      DO 317 I=1,8
  317 B(I)=Z(1,I)
C     SELECTIVE PRINT OF ANSWERS
      IF (SENSE SWITCH 1) 118,2
  118 PRINT, B(1),B(2),B(5),B(6)
      PRINT, B(3),B(4),B(7),B(8)
C     HOOP FORCE AND BENDING MOMENT IN TAPERED CYLINDER
    2 XS=XP
      I=0
      J=1
      K=5
          C1=B(1)
      C2=B(2)
      C3=B(5)
      C4=B(6)
      MAY=1
      GO TO 103
    9 I=I+1
      Z(I,J)=((E*ALPHA*XS)/A)*(C1*B(1)+C2*B(2)+C3*B(3)+C4*B(4))
      Z(I,K)=(C1*B(5)+C2*B(6)+C3*B(7)+C4*B(8))
C     PRINT OF HOOP FORCE AND BENDING MOMENT
      PRINT, XS,Z(I,J),Z(I,K)
      IF (I-7) 501,501,500
  500 I=0
      J=J+1
      K=K+1
  501 XS=XS+DELTX
      IF (XS-XL) 103,103,5
C     TOTAL STRESSES IN TAPERED CYLINDER
    5 XS=XP
      I=0
      J=1
      K=5
    3 T=ALPHA*XS
      I=I+1
      IF (I-8) 503,503,502
  502 I=1
      J=J+1
      K=K+1
  503 SXB=(6.0*Z(I,K))/(T**2)
      IF (MAY-2) 504,505,504
  504 FNT=Z(I,J)+P*A
      STO=(FNT/T)-(0.3)*SXB
      STI=STO+(2.0*0.3*SXB)
      GO TO 506
  505 STO=((P*A)/(2.0*T))-SXB
      STI=STO+(2.0*SXB)
C     PRINT STRESSES
  506 PRINT, XS,STO,STI
      XS=XS+DELTX
      IF (XS-XL) 3,3,507
```

```
  507 MAY=MAY+1
      GO TO (1,5,119),MAY
C     PRINT OF PARAMETERS
  119 PRINT, RHO,ALPHA
      PRINT, XP,XL,DELTX
      GO TO 1
      END

END OF COMPILATION
LOAD SUBROUTINE DECK
THEN PUSH START
PROCESSING COMPLETE
TO EXECUTE PROGRAM
LOAD OBJECT DECK
THEN PUSH START
```

This head is purposely designed overstrength, so that the cylinder is the main object of test. The maximum stresses occur in the crown of the head and are found from membrane theory. The discontinuity stresses near the head -- cylinder joint were discussed previously, and are not critical in the design of the head.

The actual stresses for both the 20% nickel steel and the titanium test chamber may be found in the following pages.

THE BUDD COMPANY	
PREPARED BY: EGM	PAGE NO. OF
PRODUCT DEVELOPMENT PHILADELPHIA, PA.	
CHECKED BY:	REPORT NO.
DATE: 11 JAN 62	PROJECT NO.

20" DIA. TITANIUM TEST CHAMBER

STRESSES AT HELICAL WELD:

PRINICIPLE STRESSES:

$$\sigma_\theta = \frac{pr}{t} = 1260(10)/.060 = 210,000 \text{ PSI}$$

$$\sigma_x = \frac{pr}{2t} = 105,000 \text{ PSI}$$

HELIX ANGLE:

$$\theta = 11°$$

NORMAL & SHEAR STRESSES @ WELD:

$$\sigma_n = \left(\frac{\sigma_\theta + \sigma_x}{2}\right) - \left(\frac{\sigma_\theta - \sigma_x}{2}\right)\cos 2\theta$$

$$= \frac{1}{2}(315,000 - 105,000 \cos 22°)$$

$$= 108,900 \text{ PSI}$$

$$\tau = \left(\frac{\sigma_\theta - \sigma_x}{2}\right)\sin 2\theta$$

$$= \frac{1}{2}(105,000) \sin 22°$$

$$= 19,700 \text{ PSI}$$

MAXIMUM MEMBRANE STESSES IN 1.4-1.0 ELLIPTICAL HEADER:

$$\sigma_\theta = \sigma_\phi = \frac{pa^2}{2bt} = \frac{1.4}{2}\frac{(1260)10}{.071} = 124,000 \text{ PSI}$$

OCCURS AT TOP OF HEADER

COEFFICIENT MATRIX, COLUMNS 1 TO 4

C1	C2	M(S)	Q(S)
-1.1820332E+21	-4.1763329E+21	-5.7370542E-04	3.4571957E-04
5.0411356E+21	-8.6367336E+21	-1.9040745E-03	5.7370542E-04
7.0845768E+24	-1.7262676E+24	-1.0000000	.00000000
1.5054304E+25	8.7869781E+24	.00000000	-1.0000000
-4.3985971E+23	9.8008123E+22	.00000000	.00000000
-7.9779994E+23	-5.2655513E+23	.00000000	.00000000
-1.9600179E+26	-1.0450713E+27	.00000000	.00000000
1.2851954E+27	-1.9472392E+27	.00000000	.00000000

COEFFICIENT MATRIX, COLUMNS 5 TO 8

C3	C4	M(L)	Q(L)
8.0013036E-26	-4.4711969E-26	.00000000	.00000000
-2.1186494E-25	-5.5848091E-26	.00000000	.00000000
8.6130592E-23	1.4162734E-22	.00000000	.00000000
9.7346311E-23	-3.6929231E-22	.00000000	.00000000
3.6786681E-28	5.7879988E-28	-4.0970821E-04	-2.6857352E-04
3.0278018E-28	-1.4740282E-27	1.2500176E-03	4.0970821E-04
-1.4291113E-24	9.7771454E-25	-1.0000000	.00000000
3.5977510E-24	7.3901415E-25	.00000000	-1.0000000

CONSTANTS C1 TO C4

C1	C2	C3	C4
1.1723669E-25	-2.4857781E-26	-1.4875195E+22	-3.7732181E+21

EDGE BENDING MOMENTS AND SHEARS

M(S)	Q(S)	M(L)	Q(L)
-.94212480	1.4918470	3.0165041	199.01586

TAPERED CYLINDER HOOP FORCE AND BENDING MOMENT

X	HOOP FORCE	BENDING MOMENT
16.363639	-101.40141	-.94211674
16.463639	-63.261667	-.74963466
16.563639	-26.895357	-.49374701
16.663639	8.4493996	-.21087809
16.763639	43.594217	6.3552640E-02
16.863639	79.329745	.29434898
16.963639	116.30839	.44571192
17.063639	154.95193	.48063395
17.163639	195.34849	.36046834
17.263639	237.15814	4.4836126E-02
17.363639	279.50474	-.50798983
17.463639	320.88394	-1.3402697
17.563639	359.05588	-2.4931442
17.663639	390.96346	-4.0046303
17.763639	412.64241	-5.9061954
17.863639	419.16962	-8.2192686
17.963639	404.62548	-10.949783
18.063639	362.10420	-14.082757
18.163639	283.77597	-17.575002
18.263639	161.01950	-21.347396
18.363639	-15.381966	-25.276690
18.463639	-254.88982	-29.185435
18.563639	-566.83734	-32.833703
18.663639	-959.78117	-35.908576
18.763639	-1440.8733	-38.016734
18.863639	-2014.8874	-38.676586
18.963639	-2683.2292	-37.314091
19.063639	-3442.6971	-33.261098
19.163639	-4284.0385	-25.758853
19.263639	-5190.3993	-13.967708
19.363639	-6135.7189	3.0171222

HOOP STRESSES IN TAPERED CYLINDER

X	STRESS (O)	STRESS (I)
16.363639	208781.03	207838.92
16.463639	208046.79	207306.24
16.563639	207262.43	206780.54
16.663639	206459.26	206255.91
16.763639	205668.11	205728.66
16.863639	204917.96	205195.11
16.963639	204234.88	204649.62
17.063639	203640.76	204082.76
17.163639	203152.09	203479.73
17.263639	202778.57	202818.85
17.363639	202521.45	202070.29
17.463639	202372.07	201195.33
17.563639	202309.61	200145.51
17.663639	202299.43	198862.57
17.763639	202290.63	197278.72
17.863639	202214.38	195317.50
17.963639	201981.68	192895.60
18.063639	201482.03	189925.25
18.163639	200582.21	186317.95
18.263639	199126.18	181989.37
18.363639	196935.63	176864.94
18.463639	193812.26	170888.21
18.563639	189541.22	164028.70
18.663639	183897.53	156293.96
18.763639	176653.36	147739.88
18.863639	167589.92	138485.64
18.963639	156510.77	128727.12
19.063639	143259.11	118752.42
19.163639	127739.35	108957.85
19.263639	109941.72	99862.940
19.363639	89968.900	92123.559

LONGITUDINAL STRESS IN TAPERED CYLINDER

X	STRESS (O)	STRESS (I)
16.363639	106570.19	103429.81
16.463639	105596.48	103127.97
16.563639	104535.31	102929.00
16.663639	103448.57	102770.73
16.763639	102393.65	102595.50
16.863639	101424.87	102348.71
16.963639	100594.94	101977.40
17.063639	99955.910	101429.27
17.163639	99559.850	100652.01
17.263639	99458.928	99593.205
17.363639	99704.820	98200.944
17.463639	100347.50	96425.020
17.563639	101432.92	94219.240
17.663639	103000.36	91544.160
17.763639	105077.86	88371.480
17.863639	107678.01	84688.390
17.963639	110791.24	80504.300
18.063639	114379.57	75856.960
18.163639	118368.37	70820.820
18.263639	122638.01	65515.300
18.363639	127015.52	60113.190
18.463639	131264.36	54850.860
18.563639	135077.19	50035.450
18.663639	138066.36	46054.450
18.763639	139758.91	43380.630
18.863639	139591.48	42577.190
18.963639	136910.11	44297.940
19.063639	130973.25	49284.270
19.163639	120960.95	58355.940
19.263639	105990.99	72395.040
19.363639	85141.301	92323.500

PARAMETERS

RHO	ALPHA	
30.020635	3.6666660E-03	
16.363639	19.363639	.10000000
X(S)	X(L)	DELTA X

20" DIA. NICKEL STEEL TEST CHAMBER

STRESSES AT HELICAL WELD:

PRINCIPLE STRESSES:

$$\sigma_\theta = \frac{pr}{t} = 1240(10)/.040 = 310{,}000 \text{ PSI}$$

$$\sigma_x = \frac{pr}{2t} = 155{,}000 \text{ PSI}$$

HELIX ANGLE:

$$\theta = 11^\circ$$

NORMAL & SHEAR STRESSES @ WELD:

$$\sigma_n = \left(\frac{\sigma_\theta + \sigma_x}{2}\right) - \left(\frac{\sigma_\theta - \sigma_x}{2}\right)\cos 2\theta$$

$$= \frac{1}{2}(465{,}000 - 155{,}000 \cos 22^\circ)$$

$$= 160{,}700 \text{ PSI}$$

$$\tau = \left(\frac{\sigma_\theta - \sigma_x}{2}\right)\sin 2\theta$$

$$= \frac{1}{2}(155{,}000 \sin 22^\circ)$$

$$= 29{,}000 \text{ PSI}$$

MAXIMUM MEMBRANE STRESS IN 1.4-1.0 ELLIPTICAL HEADER:

$$\sigma_\theta - \sigma_\phi = \frac{pa^2}{2bt} = \frac{1.4}{2}\,\frac{(1240)10}{.062} = 141{,}000 \text{ PSI}$$

OCCURS AT TOP OF HEADER

COEFFICIENT MATRIX, COLUMNS 1 TO 4

C1	C2	M(S)	Q(S)
-1.0908724E+08	-70423096.	-7.9436130E-04	3.9084760E-04
-58581871.	-3.5192712E+08	-3.2289305E-03	7.9436130E-04
9.1926871E+10	-1.1766374E+11	-1.0000000	.00000000
4.4303162E+11	-7.3747147E+10	.00000000	-1.0000000
-2.0543814E+10	5.8648894E+09	.00000000	.00000000
-4.0681462E+10	-2.4656585E+10	.00000000	.00000000
-1.2277150E+13	-5.8823816E+13	.00000000	.00000000
7.4572424E+13	-1.2303874E+14	.00000000	.00000000

COEFFICIENT MATRIX, COLUMNS 5 TO 8

C3	C4	M(L)	Q(L)
2.2010439E-11	4.7407521E-12	.00000000	.00000000
-3.9134262E-11	-5.5238441E-11	.00000000	.00000000
-3.7814552E-09	3.0794682E-08	.00000000	.00000000
6.9538193E-08	-4.9265074E-08	.00000000	.00000000
3.4450089E-14	6.1978780E-14	-3.3063940E-04	-2.0253952E-04
4.0865005E-14	-1.6474791E-13	1.0795168E-03	3.3063940E-04
-1.9293679E-10	1.2630724E-10	-1.0000000	.00000000
4.9827058E-10	1.2359386E-10	.00000000	-1.0000000

CONSTANTS C1 TO C4

C1	C2	C3	C4
1.6828611E-12	-4.4243205E-13	-80057963.	-1.0752595E+08

EDGE BENDING MOMENTS AND SHEARS

M(S)	Q(S)	M(L)	Q(L)
-2.8017330	.50837288	5.3688994	179.87794

TAPERED CYLINDER HOOP FORCE AND BENDING MOMENT

X	HOOP FORCE	BENDING MOMENT
5.4545454	-252.12573	-2.8017335
5.5545454	-170.65615	-2.6475425
5.6545454	-103.71163	-2.3216780
5.7545454	-49.243589	-1.8912325
5.8545454	-4.6094537	-1.4108601
5.9545454	33.053762	-.92539065
6.0545454	66.548882	-.47268279
6.1545454	98.406507	-8.6402020E-02
6.2545454	130.71485	.20144674
6.3545454	164.97777	.35845478
6.4545454	201.98209	.35030414
6.5545454	241.67428	.13999257
6.6545454	283.02955	-.31209632
6.7545454	323.93026	-1.0471740
6.8545454	361.04400	-2.1059227
6.9545454	389.71885	-3.5251452
7.0545454	403.90611	-5.3330953
7.1545454	396.12688	-7.5434858
7.2545454	357.50272	-10.147912
7.3545454	277.87174	-13.107076
7.4545454	146.01356	-16.340613
7.5545454	-49.983708	-19.715813
7.6545454	-322.20808	-23.035906
7.7545454	-682.21494	-26.027922
7.8545454	-1140.0968	-28.331122
7.9545454	-1703.3822	-29.487187
8.0545454	-2375.6487	-28.932578
8.1545454	-3154.9156	-25.995174
8.2545454	-4031.8787	-19.896371
8.3545454	-4987.8920	-9.7604802
8.4545454	-5992.8715	5.3666688

HOOP STRESSES IN TAPERED CYLINDER

X	STRESS (0)	STRESS (I)
5.4545454	306848.82	300544.92
5.5545454	303101.59	297357.18
5.6545454	298964.68	294103.90
5.7545454	294583.54	290760.38
5.8545454	290090.25	287334.78
5.9545454	285599.96	283852.83
6.0545454	281209.69	280346.51
6.1545454	276998.18	276845.49
6.2545454	273026.34	273371.06
6.3545454	269337.57	269931.81
6.4545454	265957.62	266520.49
6.5545454	262893.86	263111.99
6.6545454	260134.02	259662.23
6.7545454	257644.34	256107.87
6.8545454	255367.13	252366.70
6.9545454	253218.32	248339.23
7.0545454	251085.01	243911.35
7.1545454	248823.19	238957.96
7.2545454	246256.61	233348.70
7.3545454	243176.39	226954.79
7.4545454	239342.50	219657.95
7.5545454	234487.41	211361.57
7.6545454	228321.96	202003.16
7.7545454	220544.79	191569.59
7.8545454	210855.05	180113.82
7.9545454	198968.71	167772.47
8.0545454	184639.57	154785.43
8.1545454	167684.75	141515.41
8.2545454	148013.55	128466.24
8.3545454	125661.61	116300.55
8.4545454	100827.79	105853.80

LONGITUDINAL STRESS IN TAPERED CYLINDER

X	STRESS (O)	STRESS (I)
5.4545454	165506.50	144493.50
5.5545454	161783.50	142635.47
5.6545454	157618.98	141416.38
5.7545454	153291.36	140547.50
5.8545454	149002.39	139817.46
5.9545454	144896.62	139072.83
6.0545454	141078.27	138200.98
6.1545454	137625.24	137116.25
6.2545454	134599.88	135748.95
6.3545454	132056.81	134037.62
6.4545454	130047.79	131924.04
6.5545454	128623.96	129351.06
6.6545454	127835.50	126262.86
6.7545454	127729.02	122607.43
6.8545454	128342.90	118341.44
6.9545454	129700.44	113436.80
7.0545454	131801.45	107889.25
7.1545454	134612.33	101728.20
7.2545454	138054.53	95028.170
7.3545454	141992.73	87920.720
7.4545454	146222.22	80607.030
7.5545454	150456.43	73370.270
7.6545454	154315.97	66586.630
7.7545454	157318.96	60734.960
7.8545454	158874.27	56403.490
7.9545454	158279.44	54291.970
8.0545454	154723.05	55209.220
8.1545454	147294.49	60063.350
8.2545454	135001.76	69844.030
8.3545454	116798.72	85595.180
8.4545454	91623.310	108376.69

PARAMETERS

RHO	ALPHA
21.227796	7.3333334E-03

X(S)	X(L)	DELTA X
5.4545454	8.4545454	.10000000

CONTROLLED INGOT SOLIDIFICATION

The research work at Massachusetts Institute of Technology on controlled ingot solidification continued during the quarter. Air melted ingots of AISI 4340 steel were forwarded to U. S. Steel Corporation Research Laboratory, Monroeville, Pa. for conversion into sheet product.

Copies of M.I.T. progress reports Nos. 3, 4 and 5, covering the work accomplished during the quarter, are included on the following pages.

(COPY)

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Cambridge 39, Massachusetts

7 November, 1961

MONTHLY PROGRESS REPORT NUMBER 3

PERIOD COVERED: 1 October to 1 November

FROM: Massachusetts Institute of Technology
Division of Sponsored Research
Cambridge, Massachusetts

TO: The Budd Company
Product Development Department
Philadelphia 32, Pennsylvania

ATTN: Mr. R. C. Dethloff

CONTRACT NO.: Budd Order GHP-3912 under Prime Contract

DA-36-034-ORD-3296RD

TITAL: Solidification Control of Premium Quality Castings

WORK COMPLETED THIS PERIOD:

1. All air melted 4340 steel ingots have now been cast. Complete chemical analyses are being obtained and evaluation studies are being conducted on small sections cut from the ingots. The ingots will be shipped for forging within the next week.

2. A second unidirectional ingot was produced in the vacuum furnace. The heat was entirely successful.

Apparatus for producing unidirectional ingots in vacuum is now in complete working order and is fully satisfactory for production of ingots for shipment.

3. Melting stock originally procured for casting 25 per cent nickel-steel ingots will not be used. Budd Company has arranged for other material to be shipped to M.I.T. When this is received, ingots of the alloy will be produced.

4. The 4340 steel melting stock prepared for use in the vacuum furnace has not proven satisfactory. New melting stock is being prepared and production of these ingots is expected to begin within the next two weeks.

<u>WORK TO BE CONDUCTED DURING THE NEXT PERIOD</u>:

1. Evaluation will be continued on the ingots produced to date.

2. 4340 air cast ingots will be shipped for forging.

3. Another heat of 4340 melting stock for the vacuum furnaces will be prepared.

4. Heats of 4340 steel and/or 25 per cent nickel-steel will be vacuum melted and cast.

(Signed) M. C. Flemings
Associate Professor of Metallurgy

(COPY)

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Cambridge 39, Massachusetts

8 December, 1961

MONTHLY PROGRESS REPORT NUMBER 4

PERIOD COVERED: 1 November to 1 December

FROM: Massachusetts Institute of Technology
Division of Sponsored Research
Cambridge, Massachusetts

TO: The Budd Company
Product Development Department
Philadelphia 32, Pennsylvania

ATTN: Mr. R. C. Dethloff

CONTRACT NO.: Budd Order GHP-3912 under Prime Contract

DA-36-034-ORD-3296RD

TITLE: Solidification Control of Premium Quality Castings

WORK COMPLETED THIS PERIOD:

1. All air melted 4340 steel ingots have been shipped to United States Steel Corporation for forging and rolling.

2. Melting stock for the 25 per cent nickel-steel, including the master alloys, was received this period. The complete chemical analysis of the iron-nickel base material ingots has not yet been received.

3. Vacuum cast melting stock for the 4340 steel vacuum

ingots has been prepared. Further ingot casting has been prepared. Further ingot casting has been delayed pending results of chemical analyses.

4. Macrostructures of all air melted 4340 steel ingots have been examined; photographs of all structures have been taken. All "unidirectional" ingots were composed entirely of columnar grain extending from the bottom to the top of the ingot (as anticipated).

5. A visit was made to United States Steel Research Laboratories to discuss and establish procedures for processing controlled solidification ingots produced at Massachusetts Institute of Technology. The attached memorandum outlines conclusions of that conference.

WORK TO BE CONDUCTED DURING THE NEXT PERIOD:

1. Evaluation will be continued of ingots produced to date.

2. Additional heats will be vacuum melted and cast.

(Signed) Merton C. Flemings
Associate Professor of Metallurgy

(COPY)

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Cambridge 39, Massachusetts

5 January, 1962

MONTHLY PROGRESS REPORT NUMBER 5

PERIOD COVERED: 1 December 1961 to 1 January 1962

FROM: Massachusetts Institute of Technology
Division of Sponsored Research
Cambridge, Massachusetts

TO: The Budd Company
Product Development Department
Philadelphia 32, Pennsylvania

ATTN: Mr. R. C. Dethloff

CONTRACT NO.: Budd Order GHP-3912 under Prime Contract
DA-36-034-ORD-3296RD

TITLE: Solidification Control of Premium Quality Castings

WORK COMPLETED THIS PERIOD:

1. Three heats of the 25 per cent nickel-steel were vacuum melted and cast. Two of these were "non-unidirectional" ingots, to be rolled and tested for comparison purposes. One was cast in the special ingot mold for "unidirectional" solidification.

2. The above ingots are being analyzed chemically and metallographically.

3. Study has been continued on the ingots produced to date. Measurements are being taken of the microstructures of the 4340 air melted ingots to determine dendrite arm spacing. Procedures have been established to evaluate the inclusion content of all ingots made.

WORK TO BE CONDUCTED DURING THE NEXT PERIOD:

1. Evaluation will be continued of ingots produced to date.

2. Additional heats will be vacuum melted and cast.

(Signed) Merton C. Flemings
Associate Professor of Metallurgy

WORK CONTEMPLATED FOR THE NEXT PERIOD

Fabrication and burst test of the 20" diameter test chambers is expected to be completed during the next quarter. This estimate is based on present delivery promises for the titanium and 20% nickel steel strip, on order with prime producers.

The program being conducted jointly with Allegheny-Ludlum on evaluation of the 20% nickel steel to determine the optimum combination of cold reduction and aging temperature to yield the best mechanical properties and toughness, will be completed during the quarter. Material for this evaluation will be taken from the hot rolled band, which is in process for the 20 inch test chambers at Allegheny-Ludlum Steel Corporation. Cold reduction processing of the strip material for the 20 inch chamber will be based on results of the evaluation.

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